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Evaluation of the Magnitude and Significance of Pollution Loadings from Urban Storm Water Runoff in Ontario

Research Report No. 81

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RESEARCH REPORTS

These RESEARCH REPORTS describe the results of investigations funded under the Research Program for the Abatement of Municipal Pollution within the provisions of the Canada-Ontario Agreement on Great Lakes Water Quality. They provide a central source of information on the studies carried out in this program through in-house projects by both Environment Canada and the Ontario Ministry of the Environment, and contracts with municipalities, research institutions and industrial organizations.

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EVALUATION OF THE MAGNITUDE AND SIGNIFICANCE OF POLLUTION FROM URBAN STORM WATER RUNOFF IN ONTARIO

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RESEARCH PROGRAM FOR THE ABATEMENT
OF MUNICIPAL POLLUTION WITHIN THE
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AGREEMENT ON GREAT LAKES WATER QUALITY

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ABSTRACT

An assessment has been made of the magnitude and significance of the pollution loadings from urban runoff in the province of Ontario. The study was conducted under the provisions of the Canada-Ontario and Canada-United States Agreement on Great Lakes Water Quality.

The selected local authorities were interviewed to obtain detailed local data. In addition, various maps and demographic information were supplied by the Ministry of the Environment. Methodology used by the American Public Works Association and the University of Florida for a study of similar problems in the United States provided a basis for data manipulation and preparation of cost estimates, modified where possible to reflect conditions relevant to Ontario.

The cost estimate performed indicated that to obtain 25 percent control of BOD, an annual cost of $10,861,000 would be incurred. These costs are exclusive of the storm flow conveyance system. For BOD control at 75 percent, the annual cost would be $95,471,000.

RÉSUMÉ

Nous avons évalué l'importance de la pollution causée par les effluents urbains en Ontario, dans le cadre des accords Canada-Ontario et Canada - Etats-Unis sur la qualité des eaux des Grands lacs.

Nous avons interrogé des responsables locaux afin d'obtenir des données locales détaillées. Le ministère de l'Environnement nous a, en outre, fourni diverses cartes et informations démographiques. Les méthodes utilisées par l'American Public Works Association et l'université de la Floride pour l'étude de problèmes semblables aux Etats-Unis nous ont servi de modèle pour traiter les données et estimer les coûts. Nous les avons adaptés, lorsque possible, aux conditions propres à l'Ontario.

Nos estimations indiquent qu'une réduction de 25 p. 100 de la DBO coûterait 10 861 000 de dollars annuellement, en excluant les coûts du système d'évacuation des eaux pluviales. Une réduction de la DBO de 75 p. 100 coûterait 95 471 000 dollars par an.

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SUMMARY

In 1975 the American Public Works Association, with the University of Florida, conducted a study for the Urban Drainage Subcommittee of the Canada-Ontario Agreement on Great Lakes Water Quality.

The study was conducted by utilizing methods and procedures developed for a similar study of the United States. Information was supplied directly from the Ontario Ministry of the Environment, Environment Canada, and field interviews conducted in ten representative cities.

The characterization of urban storm water runoff and combined sewer overflows was taken from the United States study, modified slightly for conditions in Ontario. Information concerning pollution from snowmelt was obtained from Canadian studies.

Storm water modelling using the complete U.S. EPA model STORM for four small cities, and similar methods for an additional 52 cities, were used to determine storm flows and potential pollution loads. Relationships were developed between population density and pollution control costs for separate and combined sewered areas. Based upon an assumed cost and availability of land by population density, optimization of storage versus treatment was considered.

Control of pollution has been generally limited to evaluation of BOD, although other parameters are being controlled at the same time at various degrees of efficiency. The approach used could be adapted for other quality parameters.

An important aspect of water quality planning is the tradeoff involved in the decision-making process when alternatives such as providing advanced dry-weather treatment and control of storm water or combined sewer overflows are under consideration. The study indicates that a significant portion of the wet-weather pollution should be controlled prior to initiation of advanced wastewater treatment.

The study found that local officials in Ontario were very concerned with flood control aspects of storm flow and were less concerned with quality aspects. Information required for detailed individual model studies was not available, nor were plans being made to gather information on key parameters.

Thus, local officials should be made aware of the importance of pollution from urban storm water runoff and combined sewer overflows, and the significance of such polluted discharges compared to their present discharge of treated wastewater treatment plant effluents.

The storage requirements necessary to economically treat storm flow may also serve to alleviate local flooding problems. Likewise, the gathering of data for storm water modelling would be of direct benefit in the planning and improvement of the drainage system, a readily perceived benefit.

Although the cost calculations may not be accurate to a high degree for an individual city, it is believed that they are reliable for preliminary assessments when considering the total urban drainage to the Great Lakes from the province of Ontario.

CONCLUSIONS

1. City officials perceived many problems with their storm water control systems. Local flooding due to hydraulic overloading, infiltration/inflow, deposition of solids, and untreated bypasses were the most common concerns.

2. Interest in modelling storm water runoff exists, particularly with regard to quantity predictions. Most authorities appeared to not have the necessary resources to conduct studies.

3. To facilitate modelling, extensive efforts were made to characterize urban land use patterns. The distribution of developed land use in urban areas was taken as:

Residential	52.5
Commercial	10.3
Industrial	14.0
Other	23.2

4. The extent of combined sewer systems was determined for 49 of the 56 cities, based on available data.

5. The loading factors used to calculate pollution loadings were based upon a study of available applicable data. However, the overall receiving water quality impact of various sources has not been evaluated in the urban setting. Among the areas where research is minimal are: snowmelt, wear products from street surfaces, urban sediments and erosion products, tree and leaf litter, and accumulation from non-street impervious areas.

6. Primary treatment devices using physical processes such as screening, settling, and flotation have been developed and tested for application to combined sewer overflows. Their application to urban storm flows should be equally effective. BOD removal efficiency of 40 percent appears reasonable.

7. For all urban areas of over 10,000 population draining into the Great Lakes, the annual cost of providing 25% BOD removal to urban storm flow and combined sewer overflows using secondary treatment

and storage is estimated at $10,861,000, and for 50 percent control, $31,744,000.

8. Secondary treatment devices which use biological and physical-chemical processes are suitable for treating both combined sewer overflows and urban storm flow. Contact stabilization is feasible only if the dry-weather flow (DWF) facility is of an activated sludge type. BOD removal efficiency of 85 percent appears reasonable.

9. The annual cost of providing 75% BOD removal for urban storm flow and combined sewer overflows using secondary treatment and storage is estimated to be $95,471,000.

   NOTE: The above costs are in terms of 1975 dollars. Costs include land, engineering, and sludge disposal but do not include the cost of a sewer system to transport flows to the point of treatment. The primary purposes of the cost estimate were to: (1) develop an order of magnitude for the costs which might be anticipatted as control measures are required; and (2) develop a procedure for estimating costs as more refined and specific data become available.

10. Most DWF facilities offer opportunity for treating wet-weather flow (WWF). The optimum mix of facilities must be determined on a case-by-case basis.

11. The optimal cost for WWF facilities is a function of the size of the facility, the unit cost of which decreases with size, and the cost of conveying the flow to the facility, a cost which increases with the size of the facility. Such determinations must be made for specific sites. For the purpose of this study a representative treatment cost was determined.

12. The optimal sizing of treatment and storage facilities will vary for each area and for the level of control required.

13. For BOD removals of less than or equal to about 10 percent, the optimal treatment strategy is to use primary treatment devices for a portion of the flow. Secondary treatment devices will be required for higher levels of control.

14. The relationship between level of control and number of overflow events can be predicted by methods which were developed.

15. To achieve 50 percent BOD removal, intensive control of combined sewer overflows results in a lower marginal cost than control in storm sewer areas.

16. Operation and maintenance costs will be affected by the number of hours that the facility is operated. The amount of storage which is provided allows a smaller capacity treatment facility which will operate for a longer period of time to achieve the same relative treatment. For the purpose of this study, annual operation and maintenance costs have been assumed to be 20 percent of the total costs of the treatment facility. Actual costs will vary by the type and size of the individual treatment units.

17. The assumption of a first flush, a high concentration of pollutants in the first portion of the runoff, has a significant effect on cost assumptions. Control costs are about one-third less if a first flush is assumed.

18. The cost-benefit relationship between tertiary treatment of DWF and provision of WWF facilities needs to be investigated prior to instituting either control measure. When analyzed under the assumptions used in this report, it was found that about 16 percent of the storm flow should be controlled before initiating tertiary treatment if additional removal of organics is the purpose of tertiary treatment.

19. Rooftop and parking lot storage, surface and underground tanks, and storage in treatment units are effective flow attenuation control alternatives. The cost of providing such facilities varies, based upon whether or not they can be designed into new or reconstruction projects, and on the population density of the area in which they are to be located.

20. The unit costs of pollution control are lowest in the unsewered areas because of relatively low storage costs.

RECOMMENDATIONS

1. Local authorities should be made aware of the benefits of and need for urban storm flow planning for quality as well as quantity considerations. Local officials expressed concern with flooding problems but exhibited relatively minor interest in the polluting aspects of storm flow.

2. The Ministry of the Environment should take the lead in initiating storm water modelling efforts. Local officials showed an interest in modelling but generally did not have the resources to undertake such studies. The results of model studies should be of major assistance in planning for storm flow quantity.

3. Inventories of local demographic characteristics are needed, and compilation should be made to assist further modelling efforts. Such inventories should include the area served by each type of sewer.

4. Reports dealing with runoff and quality predictions should be carefully structured. Quality parameters must be precisely defined along with the averaging method used. Structured demographic data such as population density and land use should be reported for each area where studies are conducted.

5. The cost assessment methodology should be extended to cover additional storage and treatment combinations - cost and performance data for storage and treatment units, and the impact of different storage reservoir operating policies. The relationship between the number of overflow events and percent runoff controlled would be useful.

6. Careful investigation of assumptions used in this study concerning percent imperviousness is needed. Lower unit control costs may be anticipated as it is believed that conservative functions were used.

7. The tradeoff between storm flow control and tertiary treatment should be evaluated on the basis of control of pollutants other than suspended solids and BOD.

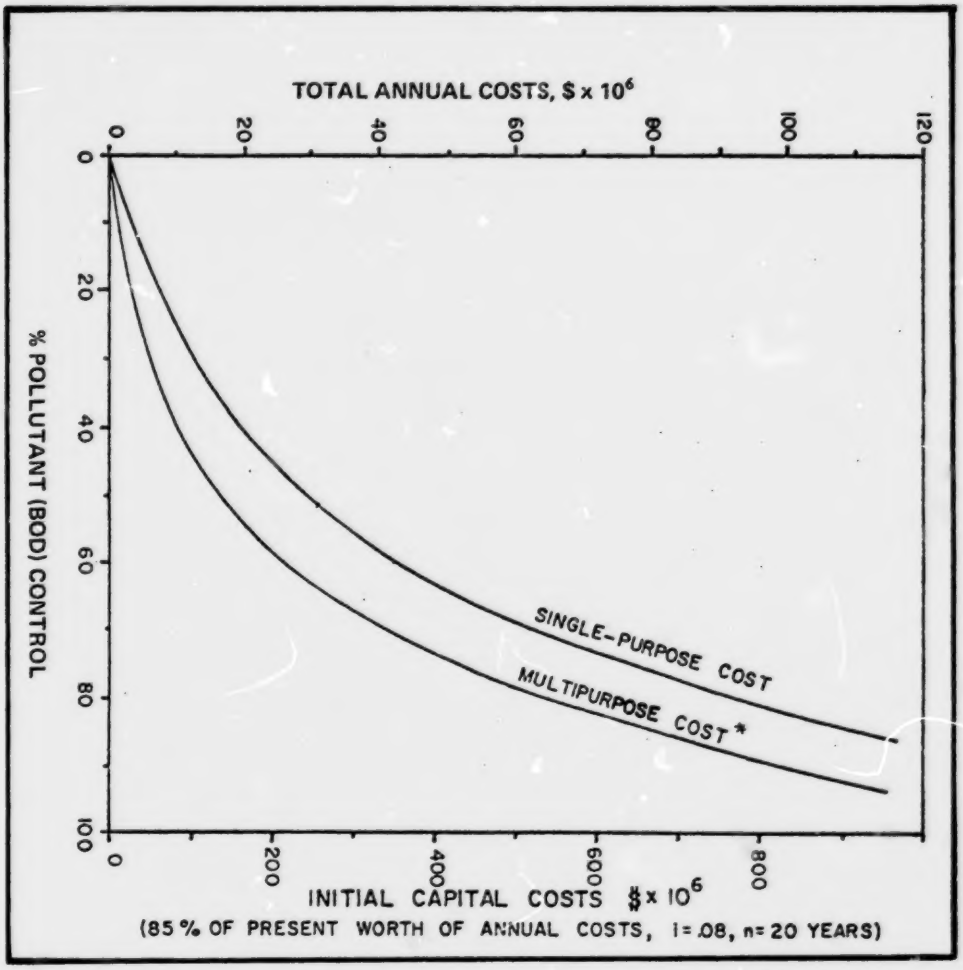
8. In conducting receiving water studies to determine the effect of urban storm flow pollution, the water quality indicators that will be used for planning purposes should be identified before the start of data collection. The data collection system must be designed to obtain representative samples before, during, and after storm events.

9. Modelling efforts require additional work. Such work should include:

   a. The response of receiving waters to urban runoff and dry-weather flow inputs should be characterized when storage of waste streams is considered in combination with treatment.
   b. Simplified techniques to approximate the complex mechanisms of pollutant transport in lakes and bays should be developed.

10. Results of present studies of runoff discharges from completely developed urban drainage basins should be carefully evaluated. Time related responses of these systems to flow and concentration for a variety of rainfall and runoff events will assist future modelling efforts in the analysis of discrete samples of runoff to provide quality information, and provide indications of runoff characterization over time.

11. The use of multipurpose units should be given consideration due to the potential cost savings. The following figure includes the estimated cost by percent pollutant (BOD) content for single purpose and multipurpose systems.



*Assumes management plan integrating dry weather quality control, wet-weather quality control, and wet-weather quantity control.

TOTAL ANNUAL AND INITIAL CAPITAL COSTS FOR VARIOUS LEVELS OF WET-WEATHER POLLUTION CONTROL IN ONTARIO

1. INTRODUCTION

1.1 Purpose

The purpose of the study was to ascertain the magnitude and significance of pollution loadings from urban storm water runoff. The three principal objectives of the study were to:

1) prepare planning estimates of the quantity and quality of urban storm water runoff contributions to the Great Lakes Ontario watershed.
2) develop cost estimates for implementing control and abatement practices with presently available technology.
3) transfer the methodology employed in the analysis to technical personnel designated by the Urban Drainage Subcommittee.

1.2 Scope

The American Public Works Association and the University of Florida have previously prepared an assessment of the pollutant effects of urban storm water runoff and combined sewer overflows [1,2,3]. Data so developed and information from the project officers, as well as from field visits to ten Ontario municipalities, were used for this study. Computer models were programmed and used to predict pollution loadings and to make overall cost assessments for various storage-treatment combinations at the downstream end of an entire urban catchment. Model outputs allow prediction of given levels of control which may be stated as:

1) percent of runoff captured,
2) percent of BOD or other pollutant removed,
3) number of overflows per year, and/or
4) quantity of overflows per year.

1.3 Background

Canada-Ontario Agreement (COA) Research Report No. 26, "Review of Canadian Design Practice and Comparison of Urban Hydrologic Models," October 1975, by J.F. MacLaren Ltd. [64], describes lucidly the concepts involved in storm water management.

"Storm water management, considering drainage as a subsystem of the total urban system with environmental aspects and possible benefits, is a relatively new concept.

"The traditional storm drainage design philosophy was to collect the runoff and carry it away as fast as possible out to the boundaries of the considered watershed. This was done by connecting all impervious areas such as roofs and driveways to a network of gutters and conduits with considerably higher velocity and density than in the natural drainage system. Storm water was also considered clean and there was no concern with regard to pollution from separate storm sewers. The design of the storm sewer system was carried on independently from the studies for flood control from rare events. Negative consequences of this philosophy, such as drastic increase of the peak flows at the outlet of the urbanized watershed, increased incidence of local flooding, depletion of groundwater, considerable increase in the cost of new storm sewerage systems and relief sewers, and the environmental damage, are now evident and many attempts for an innovative approach are underway.

"The key to the implementation of new management methods, however, is the use of improved hydrologic tools. The design of storage, for example, which is the simplest method for reduction of flow peaks, is possible only through the synthesis of hydrographs. Storage in an urban system is not necessarily concentrated in a reservoir but may be distributed over different elements of the watershed such as parking lots, roofs, elements of the sewer network, etc. Other methods of peak reduction are the retardation of flow by reduction of velocity or increase of infiltrated volumes. The traditional design method for drainage systems, the Rational Method, is aimed at providing only design peak flows and cannot be used for the study of management techniques. Even the use of the Rational Method for the derivation of design peak flows has been subject to numerous criticisms.

"Therefore, an increasing number of more sophisticated models dealing with urban storm water runoff, some of which include quality considerations, are being developed."

1.4 Runoff in General

Little doubt now exists that urban storm water runoff represents a significant source of water pollution, and affects the quality of our streams, estuaries, lakes, and oceans.

Considerable research has taken place to better understand the contamination of runoff in both urban and nonurban environments. Of particular interest, however, is urban surface runoff and its contributions to the deterioration of receiving water quality. The polluting effects of runoff may be classified in terms of direct and indirect pollution. Direct pollution includes discharges in runoff from separate storm sewer collection systems, or contributions within uncontained runoff entering the receiving water at locations other than clearly defined points of discharge.

Indirect pollution involves point discharges or overflows from the planned or unplanned addition of storm water to other wastewater flows. This may include combined sewer overflows and overflows resulting from uncontrolled runoff inflow into sanitary sewerage systems and, in some cases, excessive infiltration.

Traditionally, direct pollution from runoff has been disregarded. Surface runoff was generally characterized as a resource to be quantitatively controlled. Drainage and flood control objectives were paramount and runoff pollution was considered nonexistent or at most a low priority problem. Although early investigative efforts in Europe [4] and the United States [5] began to suggest the importance of surface runoff pollution, serious consideration of its effects is a fairly recent phenomenon. It was not until a 1964 report by the U.S. Public Health Service that the issue of runoff quality began to assume national importance [6]. In the ensuing period, a number of research efforts have sought to characterize runoff pollution, its impact, and its control and abatement.

One approach has been to empirically characterize discharges in various drainage basins across the country. This has often involved the study of drainage flows from urban or urbanizing drainage basins. On occasion, relationships between discharge and effluent quality data have been related to physical basin characteristics and given rainfall events. Inconsistency exists within this body of information, however, because of variation in research objectives being addressed, the pollutants being evaluated, the sampling techniques used and the measurements made.

These studies have identified a number of contaminating constituents. Some may demand considerable amounts of oxygen. Other constituents, such as pathogenic organisms, may produce the risk of infectious disease. Some contaminants are nutrients capable of promoting the growth of algae and aquatic plants within a receiving water. Others may be toxic to plants and animals. Still others adversely affect natural stream purification processes or give rise to sediment and solids depositions. From the subsequent water user's point of view, some pollutants cause a water supply to become hard, corrosive, or may render otherwise potable water unacceptable from the standpoint of colour,

turbidity, odour, or appearance. In the same vein, many of these constituents overtax existing water treatment facilities or make their operation uneconomical.

In an urban space, pollutants may be deposited for subsequent pickup by surface runoff or they may be directly introduced into drainage flows. The products of combustion and other suspended materials in the air (particulates and other emissions) may be scavenged from the air by falling rain. Deposits of airborne materials on pervious and impervious surfaces may be removed to contaminate runoff flows. Street paving and surfacing materials; debris from open areas, including erosion products, organic plant and animal wastes, and a variety of chemicals such as fertilizers, soil conditioners, and pesticides; transportation related material including deposits of fuel, lubricants, hydraulic fluids, coolants, tire, clutch and brake wear products, exhaust emission particulates, rust and dirt; street litter, household and commercial wastes; and finally snow and ice control, antiskid and corrosion inhibiting materials all may contribute to the contamination of runoff and its subsequent effects on receiving water quality.

Sediment is perhaps the largest single source of water pollution. Current estimates suggest that four billion tons [7] of sediment makes its way to the rivers of North America annually. Sediments are soils or other surficial materials that are products of erosion and may be transported or deposited by the action of wind, water, snow, ice, or gravity [8].

Erosion and sedimentation are natural and continually occurring geological processes. Normally, soils are protected by vegetation and vegetative residue. In areas where moisture is too limited or fertility too low to sustain close-growing vegetation, the land is subject to periodic erosion from intense rains. Man's actions, including construction and many types of urban activity, often remove vegetation in localized areas, which tends to increase the rate of erosion. Removal of the protective cover allows the forces of wind and water to act more directly and forcefully on the exposed soil particles.

Nonpoint source pollutants are organic and inorganic materials entering storm water from unspecific or unlocalized sources in sufficient

quantity to constitute a pollution problem. In a rural environment, they include sediment, plant nutrients, pesticides, and animal wastes from cropland, rangeland, pastures, and farm feedlots. Sediment is the major pollutant in terms of volume [9], and may be a carrier of some pesticides and plant nutrients. In an urban environment, similar pollutants may be experienced from impervious areas as well as those materials that are unique to urban activities, such as transportation related pollutant sources, air pollution, and so on.

A body of knowledge is now being developed through the study of some of the pollutant source characteristics previously described. Although this area of study was developed primarily for nonurban environments and nonpoint discharges, some generalizations are now being applied in urban cases to estimate pollution effects. The use of the Universal Soil Loss Equation for the estimation of sediment contributions [10] is a good example of a nonurban technology used in appropriate urban applications.

In urbanized areas, the polluting potential of street litter accumulations has been studied to assess the magnitudes of the pollutants that are available to surface runoff. Considering the developed urban street as a temporary sink for the accumulation of pollutants that are representative waste products of a complex urban environment, methods for estimating the quantity of runoff pollution have been devised under the assumptions that the urban street is a logical extension of the urban drainage system and that the runoff and polluting contributions from pervious areas will be negligible for most runoff events. This approach to the mechanism of urban runoff pollution may be construed as a special case of the study of contaminant source characteristics.

All of these methods represent some of the various mechanisms that have been used for the assessment of the direct contributions of urban runoff to pollution. The priorities associated with the evaluation, abatement, and control of indirect pollution have generally been much higher. Indirect contributions are due to the admixture of runoff with other wastewater flows. Interest in uncontrolled discharges of combined sewer overflows has generally taken the form of sampling programs, and contributions to pollution have been determined through

discharge measurements on a case-by-case basis. Similarly, the control and abatement of combined sewer overflows has been developed on a site-specific basis.

These pollution phenomena are a fact of life. They have been accepted as a matter of fact in the past and their impact on receiving waters has had an adverse effect on the water resources of the United States and Canada, and on most if not all of the developed nations.

The eventual need to control, minimize, or eliminate the polluting effects of urban and nonurban runoff wastewaters is incontestable. Yet, the costs of achieving this goal are so high that investments must be proven necessary and essential in terms of the benefits to be derived. At the same time that idealistic efforts must be made to overcome runoff pollution, further funds will be required to upgrade dry-weather wastewater treatment standards to reduce or eliminate the impacts of inadequately treated or untreated sanitary flows on receiving waters. In addition, it may be necessary to control, at least in some measure, the polluting impact of nonurban surface drainage wastes runoff on the same streams, lakes, and other water sources which are affected by wastewaters from urbanized areas.

Of overriding importance in establishing urban wastewater policies for the future is knowledge of the polluting potentials of storm water discharges, combined wastewater overflows, and dry-weather flow spill constituents, and their comparative or relative impacts on receiving waters, and also clarification of the "natural" cleanliness or pollution condition of natural streams and other receiving waters before any urban runoff waters reach them.

In order that the present study be wholly practical, commentaries on pertinent information gained from field interviews in Burlington, Guelph, Kingston, Kitchener, Milton, St. Catharines, Sault Ste. Marie, Thunder Bay, Toronto, and Windsor, are contained in Section 2.

Land use information relating to population, land area and location, and population density and land use distribution are examined in Section 3.

Utilizing such demographic information, together with pollution loading information set out in Section 4, a province-wide cost assessment

was prepared. This assessment can be improved or expanded as further data become available, as detailed in Section 5 of the report.

2. THE PROBLEM IN ONTARIO

Problems associated with receiving water pollution from urban storm water runoff have slowly become recognizable because sanitary waste discharges from local authorities have been corrected by wastewater treatment facilities. Combined sewer overflows and storm water discharges have been identified as having the potential to become a major source of pollution in receiving waters.

In Ontario it was found that few local authorities were concerned with or had identified problems associated with storm water runoff at this time. Rather, attention was primarily focused upon problems associated with flood control aspects, such as flooded basements and overloaded sewers.

2.1 Known Sewer System Problems as Perceived in the Province

On-site interviews were conducted at the ten representative cities shown in Figure 1 by a trained representative of the APWA. Officials of the Ministry of Environment were present for many of the sessions. The interview outline is contained in Appendix III. A broad range of questions were asked to determine basic information and to allow the Ministry to gain insight into local perceptions of the storm water pollution problem. The survey attempted to identify the extent of local problems with four general conditions:

a. hydraulic overloading of sewers,
b. existence of system bypasses,
c. solids deposition in sewers, and
d. infiltration/inflow problems.

Hydraulic overloading is caused by either inadequately sized sewers or excessive flows. The result of overloading is generally bypassing of treatment facilities. System bypasses allow excessive flows, or combined sewer overflows, to escape from the system without treatment. Solids deposition in sewers results from the use of large or combined sewers, flat grades or poor interior surfaces. Solids are deposited during dry weather and are then flushed out of the system during storm events. Infiltration and inflow represent a multitude of problems which allow either surface or groundwater to enter the system and contribute to

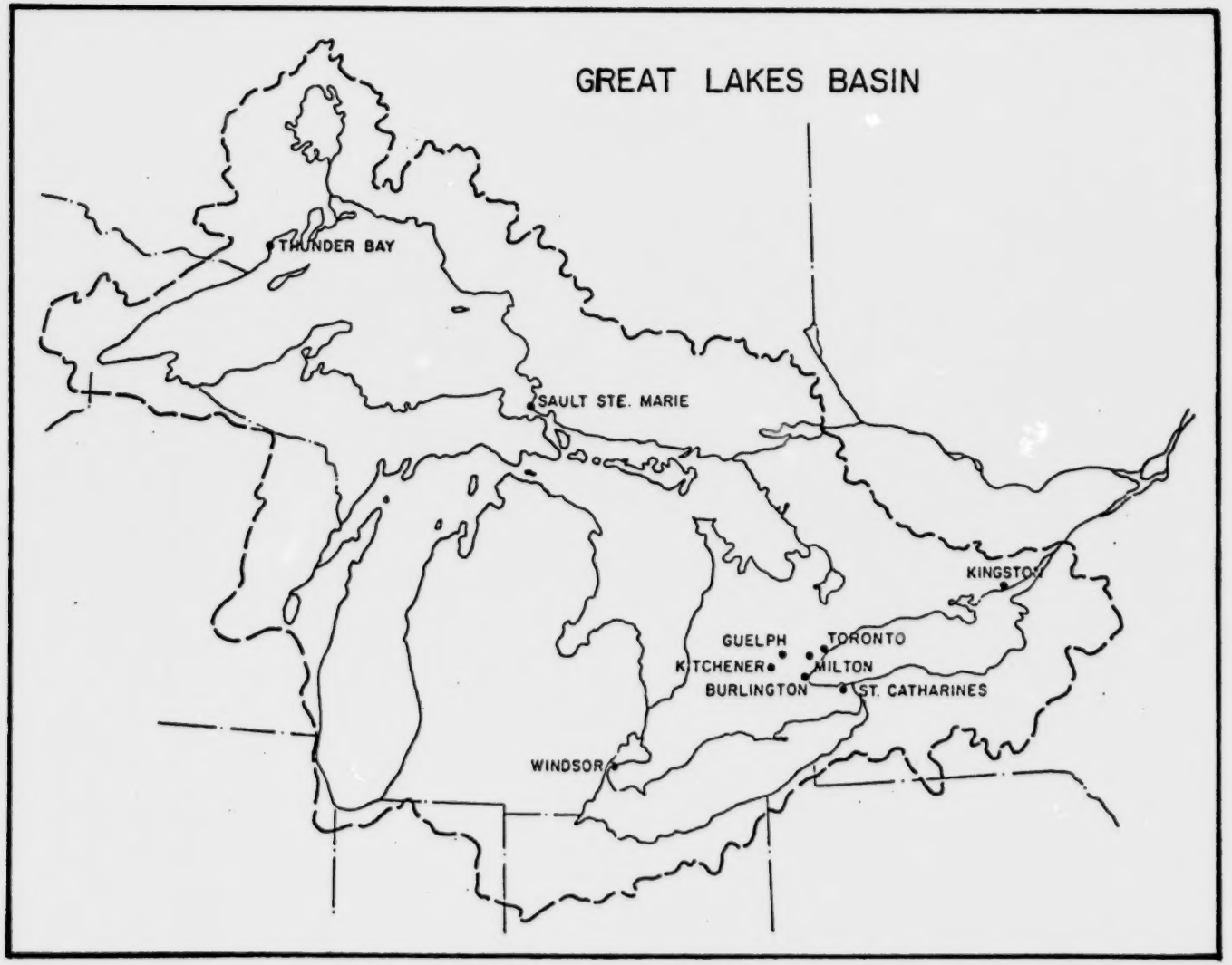


FIGURE 1 ONTARIO-GREAT LAKES BASIN TEST CITIES.

bypasses or excessive flows at treatment facilities. All of these problems may be interrelated; all affect receiving water quality.

Table 1 summarizes the responses received as either major or minor, or as not a problem. Hydraulic overloading due to size of pipe and existence of infiltration/inflow conditions appears to be the major problem.

TABLE 1. SEWER SYSTEM PROBLEM AREAS IDENTIFIED

City	Overloaded Sewers	Bypasses	Solids Deposited In Sewer	Infiltration/ Inflow
Burlington	X	-	-	X
Guelph	O	O	X	X
Kingston	-	X	O	-
Kitchener	O	-	-	X
Milton	-	-	-	X
Sault Ste. Marie	X	O	-	X
St. Catharines	X	-	O	-
Thunder Bay	X	-	X	X
Toronto	X	X	X	X
Windsor	X	X	-	X

Key: X identified general problem
O identified minor problem
- not identified as problem

Source: APWA Survey, 1975

2.2 General Comments From Field Interviews

During the course of the field interviews many relevant comments were made by local officials which are of importance in evaluating the overall problems in the province. This section will highlight the major comments.

2.2.1 Windsor

The City of Windsor encounters problems in the area known as Riverside. Riverside is served by a separate system with many interconnections. In some areas the sanitary sewer is laid directly under the storm sewer with a common manhole and a plate at the invert of the storm sewer. This leads to many problems: leakage due to improper plate replacement, missing plates, etc. Tapping into the sanitary sewer system is also very difficult.

There are a number of sewer sections that are substantially deficient in hydraulic capacity.

Storm runoff causes flooding in basements and ponding on the streets. Storm drainage facilities are inadequate in some parts of the city. Most of the sewer problems occur in early and late winter.

Windsor's past experience in receiving grant-in-aid funds has been good and the city would like to receive additional grants. City officials prefer the Central Mortgage and Housing Corporation grants because of the simple grant requirements as compared to provincial grants from Ontario Ministry of Transportation and Communication for storm water drainage projects.

2.2.2 Burlington

Burlington has established an allocation procedure for funding corrective work. However funding is considered inadequate.

Many sewers in the older areas are overloaded, primarily due to underdesign. Burlington also has serious infiltration problems. Infiltration has resulted from open joints and poor bedding. Many subdivisions were built between 1955/1960 with only sanitary sewers; open ditches are used for storm drainage.

Basement and backyard flooding in the older areas is attributed to storm sewers backing up because of high rates of inflow and infiltration. This situation generally occurs during the January thaw. As far as abatement of runoff is concerned, Burlington uses neither storage nor detention facilities. There have been no studies of storm water quality.

2.2.3 St. Catharines

The financial arrangements for storm and sanitary wastewater works in St. Catharines appear good. However, programs are cut to meet the monies available. Grants-in-aid may act as a restraint as well as an encouragement.

Hydraulic overloading shows up in areas of recurrent flooding. This is believed to be due to the undersizing of the combined sewers.

The three-year cleaning frequency of the sewers appears to be effective. There has been no concurrent improvement of receiving waters although a long-term program is under study which includes designs for watercourses.

There is no formal receiving water sampling program. There has been some effort to verify volumetric and flow gauge data obtained from their sampling activities. Local officials appeared interested in runoff planning and hoped to learn how to apply storm water management models for input to their proposed study.

Heavy infiltration/inflow is believed to be the cause of widespread flooding all over the city. The watercourses were designed with inadequate cross-sectional areas. The problem is under study with redesign planned in the near future.

The practice of building extensions on the separated sewers and then letting these sewer extensions drain into the combined sewers has only aggravated the pollution problem.

The bypassing of sewage during rainstorms is due to the hydraulic inadequacies of the system. This will be corrected by a planned program of improvement.

2.2.4 Kingston

The financial arrangements for storm and sanitary wastewater works are fair to good. The city relies generally upon the Ontario Ministry of Transportation and Communication for grants-in-aid. They have found that other grant programs involve considerable overhead and therefore they are avoided unless the advantages are substantial.

Infiltration and inflow are high, amounting to five to seven times dry-weather flow (DWF) during peak wet-weather flow periods (WWF).

The causes are probably bad joints on sewers and laterals, broken sewers, and bad backfill practices.

Basement flooding is only a minor problem because of four things: 1) the construction of additional storm sewers, 2) the elimination of the cross connections between storm and sanitary sewers, 3) disconnection of roof leaders, and 4) improved sequencing and operation of pumps.

Kingston expressed some interest in runoff planning. They had no quantity/quality management investigation planned or running at the time. They appeared to be very interested in runoff planning if Ministry-level assistance were available.

2.2.5 Thunder Bay

Monies received from the federal Central Mortgage and Housing Corporation were not substantial, about 16 percent of system expenditures. The city had great praise for the Central Mortgage and Housing Corporation and the simplicity of the grants application. Thunder Bay has experienced little difficulty in securing grants.

There are no real legal difficulties in requiring the removal of the roof leader connections. However, no attempt has yet been made to enforce removal.

There are many inadequately sewered sections of the city. Storm water collection systems have not always been installed. Basement flooding is prevalent in the Fort William area.

The city was constructing sewer system relief bypasses with the hope that such construction would eliminate the need for additional storm sewers.

2.2.6 Sault Ste. Marie

Allocation of money for storm and sanitary wastewater works in the past appears to have been at a reasonable level.

Sault Ste. Marie has no fixed program for maintenance of their sewer lines; however, the city department cleans the entire system once every three years.

Planning activities for quantity/quality had not been conducted. However, Sault Ste. Marie was very responsive to the idea of using runoff planning in the future.

Judging from the records of the wastewater treatment facility, infiltration and inflow must be assumed to be high. A general infiltration problem exists all over the city. Flooding of streets is not a serious problem.

2.2.7 Toronto

Grant experience has been satisfactory. The relief afforded by the road storm sewers is not sufficient. However, the city had not anticipated major relief from such storm sewers.

Storm water runoff causes underpasses and basements to flood, due primarily to hydraulic overloading.

Both the Metropolitan and City of Toronto governments are interested in runoff planning and would provide input to a study sponsored by the Ministry. Toronto has computer capacity and good programmers, but increased sophistication is required. Ministry assistance is, of course, a policy matter, but it is believed that a cooperative program would be well received.

Toronto presently has no runoff abatement plans. Storage or detention is not applicable at the moment and, therefore, likely locations are not known.

2.2.8 Kitchener

The City of Kitchener has enjoyed a good relationship with the federal government. Kitchener's record for applying for grants and obtaining them has been good.

A study by Proctor and Redfern, Consulting Engineers, on bottlenecks, both present and potential, in the sanitary collection system, should identify and allow correction of areas with any major solid deposition problems.

Consultants have recommended that an open storage reservoir be built in a natural catchment by damming a branch of Schneider Creek. This would in effect reduce hydraulic flows in that particular branch of Schneider Creek, and hence, act as a storage/detention basin. The basis for such a recommendation is the Grand River Conservation Authority report.

Roof leader connections are troublesome. There is a history of allowing footing drains to be connected to the sanitary sewers because the storm drains are so shallow. Insofar as the disconnection of roof leaders is concerned, enforcement has not been attempted.

There was great interest expressed in learning how to apply runoff planning tools to the Kitchener area.

2.2.9 Guelph

Guelph's past experience with the receipt of grants-in-aid has been basically good, although paperwork requirements are considered to be too extensive.

In the older areas ponding is a problem because sewers are inadequate.

The water usage per capita is increasing and relief trunk sewers may be required. It is believed that a nonlinear rate structure would help discourage excess use.

Local deficiencies are recognized in certain areas; sanitary storm sewers, infiltration and inflow, to name a few. Local officials are interested only in available runoff planning tools if the cost-benefit is apparent. Local officials would be able to produce local inputs by providing manpower for monitoring.

2.2.10 Milton

The Town of Milton has experienced severe problems with its sewerage system. The main reason is because of the incomplete system in the old part of town. This area is served by ditches and culverts. The town hopes that this problem will be eliminated in the near future.

Basement flooding is usually caused by sanitary sewers backing up through the foundation drains. There are no combined sewer overflow regulators and there are no detention facilities.

Local authorities are interested in runoff planning, but through the town's consulting engineers. As far as computer capacity is concerned, there is no available source with a sufficient memory, and they would happily accept the assistance of the Ministry of the Environment.

2.3 Climate

Climatic information was obtained which covered altitude above sea level, mean annual temperature, mean maximum daily temperatures, mean minimum daily temperatures, daily range of temperatures, extreme low and high temperatures, mean annual precipitation in inches, mean annual water

surplus in inches and mean daily temperature. Three government publications were consulted in this connection. They were: "The Climate of Southern Ontario", Climatological Studies No. 5, Environment Canada, 1974 [61]; "The Climate of Northern Ontario," Climatological Studies No. 6, Environment Canada, 1968 [65]; and "The Climate of the Great Lakes Basin," Climatological Studies No. 20, Environment Canada, 1972 [60].

A detailed listing of all the factors is included in the summary of responses from the ten cities furnished separately and is not included in this report. Selected factors are shown in Table 2. It was ascertained from a study of the climatic data that in some cases although the rainfall frequency for a particular year was typical, the snowfall was not. Because of this, one year of data from four cities, Burlington (1973), St. Catharines (1973), Kingston (1965), and Sault Ste. Marie (1969), was chosen as being typical for the computer analysis. This selection of four cities to represent the whole region was deemed adequate because of the fact that monthly precipitation below 44° latitude is very stable, while above 44° the trend is towards a peak in the summer months. Snowfall was also an important component of Ontario's precipitation total, ranging from a low of 4.0 in. (10.2 cm) water equivalent near Windsor to a high of 14.0 in. (36 cm) north of Sault Ste. Marie.

2.3.1 Windsor

From the book "The Climate of Southern Ontario" [61], the following statistics were taken for the City of Windsor. The mean annual temperature is 48°F (9°C). The extreme low temperature for the year has been recorded as -27°F (-33°C) while the extreme high temperature has been recorded at 106°F (41°C). The mean annual precipitation is 30 inches (76 cm); the mean annual snowfall is 40 inches (102 cm). The annual water surplus in inches is somewhat lower than for other parts of Ontario, being in the order of 10 inches (25 cm).

2.3.2 Burlington

In Burlington, the climatic area is described as the Lake Ontario shore. The city is at altitude of about 300 feet (91 m) above sea level. The mean annual temperature is 45°F (7°C). The extreme low temperature is -30°F (-34°C) and the extreme high is

TABLE 2. POPULATION, ALTITUDE, AREA, AND CLIMATE OF INTERVIEWED CITIES

City	Pop 1973	Area/ 1,000 acres (hectares)	Altitude feet (metres)	Annual Precipit'n inches (cm)	Snowfall inches (cm)	Days of Precipit'n	Mean Temp °F (°C)
Burlington	91,554	13.8 (5.6)	300 (91.2)	34 (86)	65 (165)		45 (7.2)
Guelph	63,009	11.3 (4.6)	1,150 (350)	33 (84)			44 (6.67)
Kingston	59,289	5.7 (2.3)	245-355 (75-108)	35 (89)			
Kitchener	121,441	22.1 (8.9)	1,100 (335)	34 (86)			44 (6.67)
Milton	15,667		650 (198)	30-38 (76-97)	48 (122)		45 (7.2)
Sault Ste. Marie	77.501	12.7 (5.1)	700 (213)	37 (94)	112 (284)		40 (4.44)
St. Catharines	112,299	16.3 (6.6)	300-800 (91.3-243)	31 (79)	45 (114)		48 (8.9)
Thunder Bay	105,954	141 (57.1)	645 (196)	29 (74)	73 (185)	141	36 (2)
Toronto	676,363	24.0 (9.7)		26.7 (68)	59.2 (150)	134	47 (8.3)
Windsor	199,250	26.3 (10.6)		30 (76)	40 (102)	137	48 (8.9)

104°F (40°C). The mean annual precipitation is 34 inches (86 cm) and the mean annual snowfall is 65 inches (165 cm). The mean annual water surplus is about 13 inches (33 cm).

2.3.3 St. Catharines

St. Catharines straddles the Niagara escarpment. This deserves special attention because of its influence on the climate of the contiguous

region. The escarpment extends from Queenston, where it is a 300 foot (91 m) bluff along the south shore of Lake Ontario through Hamilton northward to Collingwood on Georgian Bay where it is almost 8,000 feet (2,440 m) high. The annual precipitation is 31 inches (79 cm). The mean annual temperature is 48°F (9°C). The extreme low temperature is -16°F (-27°C) and the extreme high temperature is 104°F (40°C). The mean annual snowfall is 45 inches (114 cm). The altitude above sea level is approximately 300 feet (91 m).

2.3.4 Kingston

Located in Southern Ontario, Kingston's climate is moderated by the Great Lakes. Hence, Kingston's summers are cooler and winters milder than those in eastern Ontario or in the United States west of the Great Lakes. In July the mean temperature range is from 64°F to 70°F (17.7°C to 21.1°C). The corresponding mean temperature in January is 18°F to 24°F (-8°C to -4°C). The effect of the lakes, particularly in the summer when sunny days bring cool lake breezes, tends to lower the maximum temperatures. Precipitation is evenly distributed throughout the year with annual precipitation ranging from 30 to 40 inches (76 to 102 cm). The altitude above sea level is about 300 feet (91 m).

2.3.5 Thunder Bay

Thunder Bay has an altitude of 600-1,400 feet (183-427 m) above sea level. The mean annual temperature is 36°F (2°C). The mean annual minimum temperature is -40°F (-40°C). The mean annual snowfall is 73 inches (185 cm) and the water surplus is 5 inches (13 cm).

2.3.6 Sault Ste. Marie

The information obtained about Sault Ste. Marie is taken from "The Climate of Northern Ontario". The statistics are as follows: altitude, about 700 feet (213 m); mean annual temperature is 40°F (4.4°C); mean annual minimum temperature is -30°F (-34°C); the mean annual precipitation in inches is 33 (84 cm); and the mean annual water surplus in inches is 13 (33 cm). The mean annual snowfall is 112 inches (284 cm).

2.3.7 Toronto

Toronto, like the rest of the cities around the Great Lakes area, has its weather significantly altered by the Great Lakes. The usual general circulation over Ontario gives Toronto a temperature range from 10°F (-12°C) (January) to 70°F (21°C) (July) and a mean annual rainfall of 26.7 inches (68 cm). The winters are cold and dry with an annual snowfall of 59.2 inches (150 cm). The mean annual water surplus is about 11 inches (28 cm).

2.3.8 Kitchener

Kitchener is located in the climatic area known as the Huron Slope. The mean annual temperature is 44°F (6.6°C). The extreme low temperature recorded is -43°F (-42°C). The extreme high temperature is 102°F (39°C). The mean annual precipitation varies between 32 and 39 inches (81 and 99 cm). The mean annual water surplus is 6 inches (15 cm). The altitude above sea level is about 1,100 feet (336 m).

2.3.9 Guelph

The City of Guelph is also situated in the climatic region known as the Huron Slope and has a mean altitude above sea level of approximately 1,150 feet (351 m). The mean annual temperature is 44°F (6.6°C). The extreme high temperature has been 104°F (40°C).

2.3.10 Milton

The mean annual temperature is 45°F (7°C). The daily range in temperature is 18°F (10°C) in January and 22°F (11°C) in July. The extreme low temperature has been recorded as -39°F (-39°C) the extreme high is 105°F (40.5°C). The mean annual precipitation is given as between 30 and 38 inches (76 and 97 cm) of rainfall. The mean annual water surplus is 12 inches (30 cm). The mean annual snowfall is 48 inches (122 cm). The altitude above sea level is approximately 650 feet (198 m).

2.4 Wastewater Treatment and Collection Systems

Wastewater treatment facilities were also examined. As nutrient removal (phosphates) is required by Ontario regulations, most

plants are of the secondary type (activated sludge plus physical-chemical). For most of the cities examined the responsibility for wastewater treatment lies either with the provincial Ministry of Environment with costs borne by the municipality served, or with the appropriate regional government. Exceptions are Guelph, Windsor, and Kingston where all collection and treatment are city responsibilities. In Toronto, wastewater treatment is the responsibility of the Municipality of Metropolitan Toronto. Table 3 shows the prevailing situation.

A summary by cities of treatment plant type, hydraulic capacities and percentage removal of pollutants is included in Table 4.

Receiving waters are as follows:

Windsor	Detroit River to Lake Erie
Burlington	Lake Ontario
Kingston	Cataraqui River to Lake Ontario
Thunder Bay	Kaministiqua River to Lake Superior
Sault Ste. Marie	St. Mary River to Lake Huron
Toronto	Don and Humber Rivers to Lake Ontario
Kitchener	Schneider Creek and Speed River to Lake Erie
Guelph	Eramosa River to Lake Erie
Milton	16 Mile Creek to Lake Ontario
St. Catharines	Creeks to Lake Ontario

2.4.1 Windsor

Windsor is basically served by two sewage treatment plants. One is served by combined sewers; the other is served by separate sewers. The one located in West Windsor has a capacity of 21 Imgd (1104 L/sec) while the other, located in Little River, Ontario, has a capacity of 4.5 Imgd (236 L/sec). The Little River is an activated sludge plant with phosphorus removal. Dry-weather flow goes directly into the interceptor sewer.

The West Windsor plant has summary treatment along with phosphorus removal. The Little River plant is equipped with pumping stations, grit chambers, sedimentation basin, aeration tanks, secondary sedimentation, vacuum filters, and centrifugation.

TABLE 3. RESPONSIBILITY FOR SEWER SYSTEM

City	Sanitary Sewers	Storm Sewers	Combined Sewers	Wastewater Treatment
Windsor	City	City	City	City
Burlington	Region (Halton)	City	N/A	Region
St. Catharines	Region (Niagara) & City Depending on size	City	Shared	Region
Kingston	City	City	City	City
Thunder Bay	Ministry of Environment	City	City	Ministry of the Environment
Sault Ste. Marie	City	City	City	Ministry of the Environment
Toronto	Shared according to size with Mun. of Metro Toronto	Shared	Shared with Metro Toronto	Metro Toronto
Kitchener	City	City	City	Region (Waterloo)
Guelph	City	City	N/A	City
Milton	Region (Halton)	Town	N/A	Region

TABLE 4. SUMMARY OF WASTEWATER TREATMENT FACILITIES

City	Type of Treatment	Number of Plants	Total Mean Daily Flow Treated (Imgd)	Total Mean Daily Flow Treated (m^3/s)	Efficiency of Removal BOD_5 (%)	Efficiency of Removal SS (%)	Efficiency of Removal Nutrients (%)
Burlington	Activated Sludge	3	1.57	0.083	94.5	90.8	55.4
			10.6	0.557	85.6	78.3	82.4
			1.55	0.08	55.4	40.8	27.1
Windsor	Primary	2	22.1	1.16	48.0	62.0	70.0
	Activated Sludge		5.0	0.263	74.0	80.0	41.0
St. Catharines	Activated Sludge	2	15.4	0.81	86.2	90.5	58.9
	Primary				57.0	47.6	12.8
Kingston	Primary	1	11.0	0.58	50.0	75.0	-
Thunder Bay	Primary	2	6.01	0.32	23.0	49.0	22.0
			6.20	0.33	22.0	52.0	28.5
Sault Ste. Marie	Primary	1	9.90	0.52	43.0	66.0	38.0
Toronto Metro	Conventional Secondary	3	69.0	3.63	96.0	95.0	87.0
			176.0	9.26	82.0	91.0	93.0
			8.1	0.43	87.0	93.0	-
Kitchener	Primary	1	14.3	0.75	89.0(?)	90.0(?)	-
Guelph	Conventional Secondary	3	Not Operating		-	-	-
			3.0	0.16	77.0	90.5	-
			3.0	0.16	81.5	93.0	-
Milton	Conventional Secondary	1	1.0	0.053	89.7	94.7	-

2.4.2 Burlington

The sanitary wastewater works in Burlington were recently turned over to the regional government. The operation and maintenance of the storm sewer system is the responsibility of the city. The operation and maintenance of the sanitary sewer system is the responsibility of the region. There are no combined sewers in Burlington, but there are separate storm sewers and open channels. At the time there were no detention or retention facilities.

The mean daily flows in Burlington's three wastewater treatment plants are 1) Drury Lane, 1.57 Imgd (82 L/sec); 2) Skyway, 10.6 Imgd (552 L/sec); and 3) Elizabeth Gardens, 1.55 Imgd (81 L/sec). The treatment unit processes that they employ are: 1) Drury Lane-conventional activated sludge; 2) Skyway - extended aeration, aerobic digestion, and sludge thickening; and 3) Elizabeth Gardens-conventional activated sludge.

2.4.3 St. Catharines

In the City of St. Catharines there are two types of sanitary sewers: regional trunk sanitary sewers and local sanitary sewers. The wastewater treatment plant is solely the responsibility of the region with charges being made on a user basis. The operation and maintenance of the storm sewers is the responsibility of the city. All the pumping stations are maintained by the region at the cost of the city.

Regulator facilities are set to overflow when the wet-weather flow exceeds 2.5 times the dry-weather flow. There is no detention. However, the city has developed a project proposal for evaluation of the performance of a combined wastewater retention facility. In areas where there are combined sewers, restricting runoff from roofs and holding on open spaces is practiced.

The Port Weller treatment plant has a mean daily flow of 15.4 Imgd (810 L/sec). The Port Weller treatment process is activated sludge, while Port Dalhousie has a primary treatment unit.

2.4.4 Kingston

For Kingston, the wastewater treatment works' capacity is about 19 Imgd (990 L/sec). Treatment unit processes consist of pumping stations, grit chambers, sedimentation tanks, and digesters. The effluent is chlorinated and discharged into Lake Ontario.

Effluent strength for BOD is between 5-100 mg/L. Nutrients are about 5-7 mg/L and are mostly phosphates. The efficiency of the treatment process is approximately 5-50 percent for BOD and 75 percent for suspended solids.

Limited size detention tanks were under consideration. Chlorination is proposed if the detention tanks are used, but there were no current plans for the wastewater treatment plant. The average flow for the plant is 11.0 Imgd (578 L/sec). Primary treatment with separate sludge digestion is used.

2.4.5 Thunder Bay

In Thunder Bay the sanitary wastewater works are the responsibility of the Ministry of Environment of Ontario with the sanitary wastewater sewers being designed by the city and operated by the Ministry. The design, construction and operation of the sewage treatment plant is also the responsibility of the Ministry. Thunder Bay has two wastewater treatment plants, South Plant, 6.01 Imgd (314 L/sec) and North Plant, 6.20 Imgd (324 L/sec). Expansion of the South Treatment Plant was underway and the North Plant was to be abandoned shortly thereafter. The South Treatment Plant contains screening, pumping, grit removal, primary sedimentation, chlorination, and two stage separate sludge digesters. No detention facilities were planned at the time.

2.4.6 Sault Ste. Marie

Sault Ste. Marie is served by a separate storm sewer and a sanitary sewer running side by side and entering a common manhole.

The wastewater treatment plant and the pumping stations are maintained by the Ministry of the Environment. Insomuch as dry-weather treatment is concerned, effluent flows can be adjusted from the lift stations as necessary, and through the bypass capability; these are used for emergency purposes less than once a year.

There are no detention facilities in use with the exception of a conservation scheme known as the Fort Creek Conservation Dam. There are no control activities for wet-weather flow.

The mean daily flow is 9.90 Imgd (516/L sec). The plant uses comminution, grit removal, primary sedimentation, and chlorination as treatment processes.

2.4.7 Toronto

In Toronto, there are two classes of sewers: those that are owned and operated by the city, and the Metro sewers. The Metro sewers are all trunk sewers that serve 1,000 acres (405 ha) or more. The city sewers come under the jurisdiction of the Department of Public Works of Toronto. All the wastewater treatment works are controlled by the Metro Corporation and the same division prevails for operations maintenance and capital construction.

Ninety-five percent of the city is served by combined sewers. There is a separate sewer district covering Swansea (discharges into the Humber plant) and Forest Hill Village (discharges into the Toronto system).

There were no wet-weather control activities at the time. The mean daily flows in Toronto's three wastewater treatment plants are: 1) Humber, 69.0 Imgd (3,600 L/sec); 2) Main, 176.0 Imgd (9,260 L/sec); and 3) North, 8.1 Imgd (426 L/sec); all employ conventional secondary treatment.

2.4.8 Kitchener

In Kitchener all sewers are the responsibility of the city. The treatment works are the responsibility of the regional government. The sewage treatment plants, all of which are called regional, are, for all intents and purposes, provincial sewage treatment plants. There are very few combined sewers, as there are separate sanitary and storm sewer systems. The treatment plant has been under continuous expansion.

Two pumping stations have bypasses to the rivers. The sewage treatment plant bypass operates only when a breakdown takes place. The effluent is chlorinated. Storage methods are not used. None of the other techniques, such as tanks or detention facilities, are employed. The mean daily flow in the Kitchener wastewater treatment plant is 14.3 Imgd (746 L/sec), utilizing secondary treatment.

2.4.9 Guelph

Guelph has the responsibility for the design and construction of the storm water facilities. The city is also responsible for the wastewater treatment works. This is unusual in Ontario. The plant is a secondary treatment plant with phosphorus removal. In addition, the

effluent is chlorinated. Operation and maintenance of the plant, as well as the storm and sanitary sewer systems, is the responsibility of the city.

Wastewater treatment works handle a mean daily flow of about 8.5 Imgd (433 L/sec) and peak is somewhat higher. The flow is gravity fed to the plant, which is a conventional activated sludge plant. Actually, there are three plants in Guelph, but all are at one geographical location. One has a capacity of 2 Imgd (104 L/sec) and is the oldest of the plants; two newer plants have a capacity of 4 Imgd (208 L/sec). The 2 Imgd (104 L/sec) capacity plant is presently held as a standby. Detention and retention basins were expected to be constructed during the 1975-1976 season.

2.4.10 Milton

Milton has a conventional activated sludge plant, with tertiary treatment using lime. This treatment process is a regional responsibility. The rated capacity is 1.58 Imgd (82.4 L/sec); the average daily flow is 1.0 Imgd (53 L/sec). The raw sewage has a five-day BOD of 151 mg/L, suspended solids of 195 mg/L, nitrogen of 51 mg/L, and a phosphorus total of 7.5 mg/L. The final effluent has a five-day BOD of 6.5 mg/L, suspended solids of 24 mg/L, nitrogen of 7.5 mg/L, and phosphorus of 2.9 mg/L. The percentages of removal are therefore 95.6, 37.7, 85.3, and 61.3, respectively, for five-day BOD, suspended solids, nitrogen, and phosphorus. The Ministry of the Environment is committed to allowing a connected population of 18,000 persons to contribute to the existing plant. Milton has established a subdivision priority list to increase the population to 18,000. A further expansion to 2.84 Imgd (148 L/sec) will allow for an additional 10,000 persons. Treatment facilities at the plant are very erratic due to pulsing caused by effluent pumps.

There are no wet-weather controls and detention facilities in Milton at this time. The town, however, still physically operates and maintains its own sewers.

2.5 Development Characteristics

Key city development characteristics are listed in Table 5. As noted, most cities have considerable industry.

TABLE 5. DEVELOPMENT CHARACTERISTICS

City	Major Industries	Growth Expected
Windsor	Automotive (Primary) Distilling	Moderate
Burlington	Secondary types Steel	Uniform
St. Catharines	Secondary Automotive Agricultural Electronic	Moderate
Kingston	Sparse with aluminum and paint industries in adjacent township	Small
Thunder Bay	Grain shipping & storage Pulp & Paper Steel & Iron	Moderate
Sault Ste. Marie	One prominent industry Steel	Uniform
Toronto	Almost every conceivable type of industry (primary and secondary) and commercial endeavor	Uncertain due to political development disputes
Kitchener	Furniture manufacturing Automotive (secondary) Rubber Meat Packing Shoe manufacturing	Brisk
Guelph	Diversified secondary	Steady - at about 4% p.a.
Milton	Steel (secondary)	Brisk

2.5.1 Windsor

Situated across the river from the city of Detroit, Windsor is Canada's counterpart of Detroit as an automotive center. Ford, Chrysler, General Motors, and American Motors plants are in the city. Windsor is also a distilling center. There are light support industries and the University of Windsor within the City boundaries.

2.5.2 Burlington

In Burlington, secondary industries predominate, along with service industries of the "clean" type. Slater Steel was expected to come into Burlington in late 1975. Population growth is expected to stay uniform.

2.5.3 St. Catharines

St. Catharines is strongly supported by the automotive industry. There are some electronic plants, a winery, and canning and agricultural industry sidelines. The construction industry is prominent. The western part of the city is devoted to agricultural use, fruit raising and vineyards, some sparse commercial and industrial uses, and some suburban-type residential development. There are no utilities other than electric and communication. The built up area contains mixed commercial, industrial, and residential developments.

2.5.4 Kingston

Kingston has little local industry. There is a sparse amount of light industry including a dairy. Kingston is a university center and includes Queen's University, The Royal Military College of Canada, and St. Lawrence Community College. It is also a tourist and historical center, serving the Thousand Island region in the St. Lawrence River.

2.5.5 Thunder Bay

Thunder Bay is one of Canada's main grain shipping ports. There are four large pulp and paper mills, a major steel and iron fabricating manufacturing plant, and some chemical manufacturers. Industrial support industries include saw mills, a malting plant, and an industrial grain product plant.

The city is a tourist center and serves as gateway (eastern) to northwestern Ontario. It is well supplied with service industries and is the location of Lakehead University and Confederation College. It has shipyards.

2.5.6 Sault Ste. Marie

Sault Ste. Marie is virtually a one industry town with a steel company dominating. Smelted ore is shipped by rail and water to Sault

Ste. Marie from Wawa to the North, and from the Mesabi and Atikokan ranges to the west by rail and water. There is a local iron foundry and numerous service industries.

2.5.7 Toronto

In Toronto, one of the most difficult things is predicting changes in land use because of the development dispute that is going on in the various segments of the city. Toronto has a very wide diversity of land use. Residential density varies from a few persons per acre in such communities as Rosedale to as high as 600 persons per acre (1,480 persons per hectare) in St. James Town. Toronto is also an important transportation centre and a port city. The City of Toronto is distinct from Metro Toronto, which is responsible for a variety of area-wide services. Major economic activities may be described as business, commerce, manufacturing, transportation, which literally cover the entire field of production of modern goods and services, Toronto being the prime supplier for all of Canada.

2.5.8 Kitchener

Kitchener is a heavily industrialized city. Major economic activities include furniture manufacturing, automotive manufacturing, tire manufacturing, meat packing, shoe manufacturing, and other industries. Commercial activities are average, as are service activities.

2.5.9 Guelph

Guelph contains a wide range of commercial, industrial, and cultural activities. A sound economic base is apparent. Present indications suggest that the population should reach 130,000 by the year 2000. The population of Guelph is increasing at an annual rate of about four percent. The northwest area of the city has not been developed while the remainder of the city has been developed.

2.5.10 Milton

Development pressure is very heavy for the Town of Milton. The urban area of Milton still contains about 90 percent agricultural open space. Major activities in the area include a screw fastening company and a steel products company. There are many other smaller industries scattered throughout the town.

2.6 Summary

Four main problems, namely, hydraulic overloading, system bypassing, solids deposition, and infiltration/inflow in the ten Canadian cities were confirmed. Undoubtedly there are many other problems such as flooding and runoff, but the problems commented upon in this report appeared to be most prevalent in almost all the cities of Ontario.

Broadly characterized, the problems which appeared to exist are common to many cities in the United States. Inasmuch as there has not previously existed a major reason for attention to many of the problems of sewer overloading, bypassing, and such, little attention apparently has been given to the sewer system, the buried "conducts of civilization".

The general opinion was that grants can act either as a restraint or as an encouragement. When a grant policy is in effect, programs are designed according to the availability of funds. A summary of Federal and Provincial Grant regulations is contained in Appendix IV. Local authorities have generally had favorable experience with Federal (CMHC) and Provincial (MOT&C) grants.

Interest in runoff planning and management was at a high level and all communities seemed willing to cooperate with the technology transfer proposed and would provide input wherever possible. Most, however, were unable to provide computer capacities for the recently available storm water runoff models such as STORM [11].

Most communities did not have storm water quality/quantity management programs in operation although some work was being carried out by consultants.

3. DESCRIPTION OF THE URBAN AREAS

This section presents a summary and analysis of data on the following characteristics of urban areas within the portion of Ontario located in the Great Lakes Basin:

1) population, land area, and location; and
2) population density and land use distribution.

3.1 Definition

Urban areas in this study have been defined as:

1) an incorporated city or urban core of 10,000 or more inhabitants; or
2) an agglomeration of census tracts with population densities of one or more persons per acre.

Using information found in the "1971 Census of Canada", Statistics Canada [12], a total of 56 urban areas were defined. The resulting population and land area for each urban area are shown in Table 6. In order to characterize all of the urban areas in the study area, ten test cities were chosen before the study was initiated: Burlington, Guelph, Kingston, Kitchener-Waterloo, Milton, St. Catharines, Sault Ste. Marie, Thunder Bay, Toronto, and Windsor. Milton was not used due to its small population. Toronto was characterized by a section of that municipality know as West Toronto, except for the determination of population density groups, in which the entire city was used. The location of these test cities is shown in Figure 1.

3.2 Population Density and Land Use Distribution

The overall population density for an urban area may be obtained using the data in Table 6. In general, population densities have decreased during the past generation, reflecting the availability of improved transportation systems, the desire for individual home ownership, etc. No detailed data on urban land use for all of the urban areas could be found. For the nine urban areas (see Appendix II for maps), the area occupied by each of the following five types of land uses was determined: residential, institutional, industrial, commercial, and open space. Land use maps were unavailable. Aerial photographs were

TABLE 6. DEMOGRAPHIC CHARACTERISTICS OF THE URBAN AREAS

NO	URBANIZED AREA	1000 ACRES	1971 POP 1000	POP AVE PD
1	AJAX	2.86	12.52	4.38
2	AURORA	6.86	11.28	1.64
3	BARRIE	7.16	27.68	3.87
4	BELLEVILLE	5.94	35.13	5.91
5	BRAMPTON	5.81	41.21	7.09
6	BRANTFORD	9.48	63.88	6.74
7	BURLINGTON	13.81	80.60	5.84
8	CHATHAM	5.46	35.32	6.47
9	CHINGUACOUSY	2.08	22.10	10.62
10	COBOURG	2.89	11.28	3.90
11	DUNDAS	3.47	17.21	4.96
12	ETOBICOKE	30.62	282.69	9.23
13	GALT	8.32	38.90	4.68
14	GEORGETOWN	3.08	17.05	5.54
15	GUELPH	11.30	56.57	5.01
16	HAMILTON	26.05	305.65	11.73
17	KINGSTON	5.68	59.00	10.39
18	KITCH.-WATERLOO	22.07	147.86	6.70
19	LEAMINGTON	2.01	10.44	5.19
20	LINDSAY	3.78	12.75	3.37
21	LONDON	33.17	220.90	6.66
22	MARKAM	6.11	16.19	2.65
23	MIDLAND	3.40	10.99	3.23
24	MISSISSAUGA	23.62	150.33	6.36
25	NEWMARKET	9.02	18.94	2.10
26	NIAGRA FALLS	10.86	62.71	5.77
27	NORTH BAY	2.26	23.64	10.46
28	OAKVILLE	9.99	54.69	5.47
29	ORILLIA	5.66	24.04	4.25
30	OSHAWA	13.61	91.59	6.73
31	OWEN SOUND	6.04	18.47	3.06
32	PETERBOROUGH	10.81	57.79	5.35
33	PICKERING	5.09	19.06	3.74
34	PORT COLBOURNE	5.22	17.99	3.45
35	PORT ERIE	2.00	11.65	5.82
36	PRESTON	4.22	16.72	3.96
37	RICHMOND HILL	10.20	26.26	2.57
38	ST. CATHARINES	16.33	107.19	6.56
39	ST. THOMAS	4.49	25.54	5.69
40	SARNIA	4.69	57.02	12.16
41	SLT. STE. MARIE	12.71	70.62	5.56
42	SCARBOROUGH	31.94	331.16	10.37
43	SIMCOE	2.28	10.79	4.73
44	STRATFORD	5.02	24.51	4.88
45	SUDBURY	23.95	90.48	3.78
46	THUNDER BAY	14.10	97.17	6.89
47	TORONTO	24.01	712.79	29.69
48	TRENTON	2.53	14.59	5.77
49	WALLACEBURG	2.58	10.55	4.09
50	WELLAND	9.77	41.72	4.27
51	WHITBY	4.42	16.76	3.79
52	WINDSOR	26.32	200.95	7.63
53	WOODSTOCK	6.04	26.17	4.33
54	YORK	5.73	147.30	25.71
55	YORK, EAST	5.25	104.78	19.96
56	YORK, NORTH	43.71	504.15	11.53
	TOTAL	585.88	4725.31	8.07

employed if land use maps were unavailable. These photos presented a problem, in that they were taken at altitudes (1.6 miles or 2.6 km, approximately) that made differentiating among land uses difficult.

The percentage of the land use in each of these five categories is shown in Table 7. Note that, with the exception of West Toronto which has a very high average population density (29.7 persons per acre), a large percent of the urban area falls in the open space category. This large amount of open space resulted from the definition of urban areas, which included population densities as low as one person per acre. Thus, significant acreages of land which were undeveloped and would not be served by sewerage systems were included.

TABLE 7. LAND DISTRIBUTION IN NINE ONTARIO CITIES

Urbanized Area	Population Density persons/acre	Percent of Urbanized Area in Indicated Land Use					
		Residential	Commercial	Industrial	Institutional	Open	Total
Burlington	5.84	34.0	3.0	3.0	5.0	55.0	100
Guelph	5.01	29.0	3.0	8.0	6.0	54.0	100
Kingston	10.39	32.0	5.0	7.0	12.0	44.0	100
Kitchener-Waterloo	6.70	27.0	4.0	10.0	2.0	57.0	100
St. Catharines	6.56	41.0	4.0	6.0	6.0	43.0	100
Sault Ste. Marie	5.56	40.0	4.0	19.0	4.0	33.0	100
Thunder Bay	6.89	34.0	13.0	12.0	6.0	35.0	100
Toronto, West	29.69	58.0	19.0	14.0	4.0	5.0	100
Windsor	7.63	38.0	6.0	10.0	3.0	43.0	100
Average, area weighted	10.47	38.4	7.6	10.3	4.5	39.3	100

Manvel et al [13] present data on land use in 106 United States cities. Analysis of these data indicates that the proportion of the urban area in each land use category was relatively similar after deducting the proportion of the urban area which is in the undeveloped category. This category is deducted from the total urban area to obtain the developed portion of the urban area. Figure 2, shows the percent undeveloped land as a function of population density for the U.S. cities and the percent open land for the Ontario cities. The open category would include undeveloped land and developed open space land, e.g., parks. As can be seen from Figure 2, the Ontario cities generally fall above the line of best fit for the U.S. undeveloped land. This result

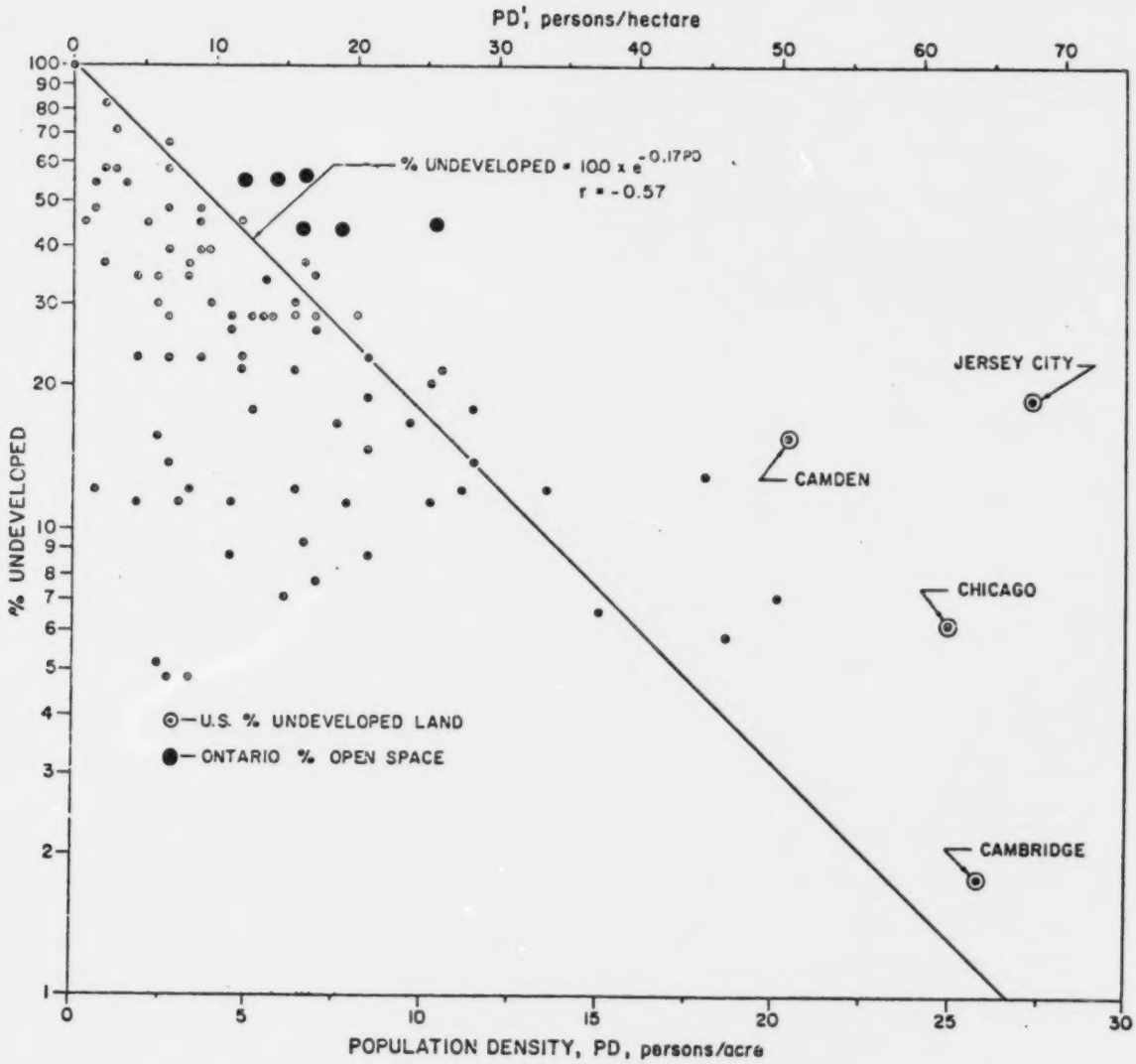


FIGURE 2. PERCENT UNDEVELOPED LAND USE (U.S.) AND OPEN SPACE LAND USE (Ontario) VERSUS POPULATION DENSITY

Note that best fit line is forced through 100 percent at PD=0

appears reasonable since the open space category would include the undeveloped land. Thus, it seemed reasonable to use the U.S. equation to estimate the percent of the urban area which is undeveloped, i.e.,

$$Z = 1.0e^{-0.170(\overline{PD})} \qquad (r = -0.57) \qquad (1)$$

where: Z = proportion undeveloped land,

PD = average gross (developed and undeveloped) population density, persons per acre, and

r = correlation coefficient ($-1.0 \leq r \leq 1.0$).

Using this relationship, the developed population density, PD_d, can be expressed as a function of the gross population density using

$$PD_d = \frac{PD}{(1-Z)} = \frac{PDe^{0.17\ PD}}{e^{0.17\ PD_{-1}}} \qquad (2)$$

Equation (2) is shown in Figure 3. Note that the developed population density is about six persons per acre at the lowest level of urbanization (one person per acre). The developed population density approaches the gross population density as PD increases. Indeed, they are quite close at $PD \geq 25$ persons per acre.

After correcting for the percent undeveloped, the proportion of the land in the developed uses was determined as a percent of developed urban land only. After this transformation was made, the percent of land in the developed uses seemed to be independent of population density. The resultant distribution of developed land by use and undeveloped land is shown in Table 8. Note the similarity of the Ontario and U.S. land use distributions.

The land distributions for all cities are determined using equation (1) and Table 8. The results are presented in Table 9. In determining the control costs, only the developed portion of the urban area is considered. Thus, it is important to check the validity of this assumption in future assessments. Actual field data need to be gathered and analyzed using a consistent set of assumptions regarding land use categories.

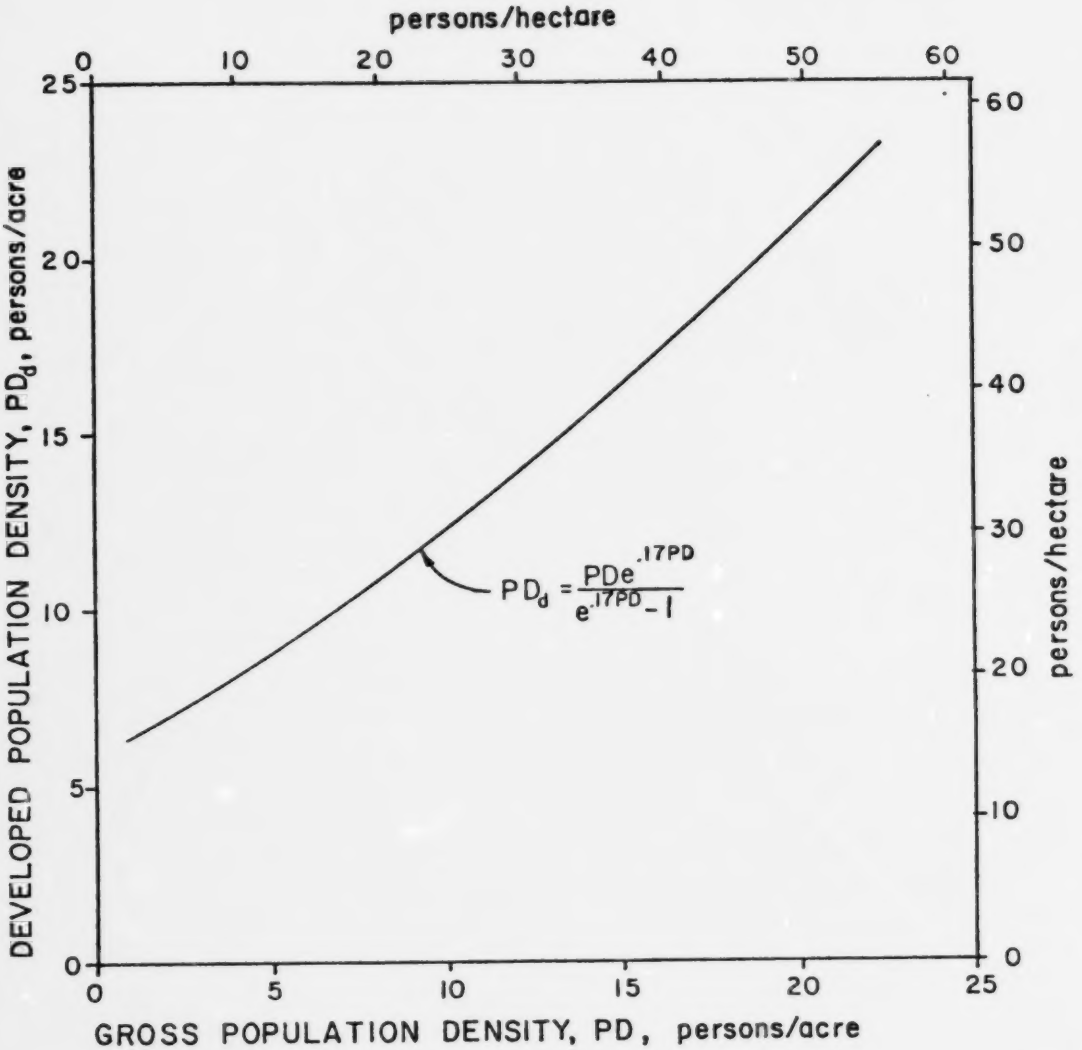


FIGURE 3. RELATIONSHIP BETWEEN GROSS AND DEVELOPED POPULATION DENSITY

3.3 Population and Area Served by Type of Sewer System

The area served by combined sewers was determined by on-site interviews in the nine cities, a survey by Waller [14], and questionnaire results from a 1966 survey [15]. These three sources provided estimates for 49 of the 56 cities. The remaining seven cities were assumed to have the same percentage of combined sewers as the other 49 cities, which is

TABLE 8. DISTRIBUTION OF DEVELOPED LAND USES IN ONTARIO TEST CITIES AND U.S. CITIES

Land Use	Percent of Total	
	Ontario	U.S.[b]
Residential	52.5	58.4
Commercial	10.3	8.6
Industrial	14.0	14.8
Other[a]	23.2	18.2

[a]Recreational, schools and colleges, and cemeteries

[b]Heaney, J.P., W.C. Huber, et al., Nationwide Evaluation of Combined Sewer Overflows and Stormwater Discharges: Volume II, Cost Assessment and Impacts, U.S. EPA 600/2-77-064, 1977.

very close to 25 percent. Unfortunately, much of the data expressed the combined sewered areas as a percent of total sewered area, which is unknown. Also, no data were available regarding population served by the combined sewer systems. Thus, indirect estimating procedures were used as discussed below.

Information was obtained regarding the population density distributions of the nine test cities. Using these data, the census tracts were ranked by population density and grouped into five categories ranging from lowest density to highest density as shown in Table 10. A histogram for the city of Thunder Bay is shown in Figure 4.

An equation of the form

$$PD = ax^b \tag{3}$$

where: PD = gross population density, persons per acre ($PD \geq 0$),

x = percent of urban area ($0 \leq x \leq 100$), and

a,b = parameters,

was fit to these data. The average population density in any interval, x_1 to x_2, is

$$PD_{x_1 - x_2} = \frac{1}{x_2 - x_1} \int_{x_1}^{x_2} ax^b dx. \tag{4}$$

TABLE 9. LAND USE DISTRIBUTIONS FOR THE ONTARIO CITIES

NO	URBANIZED AREA	LAND USE AS % OF TOTAL AREA					
		UNDV	RES	COMM	INDL	OTH	TOTAL
1	AJAX	47.5	27.6	5.4	7.3	12.2	100.0
2	AURORA	75.6	12.8	2.5	3.4	5.7	100.0
3	BARRIE	51.8	25.3	5.0	6.7	11.2	100.0
4	BELLEVILLE	36.6	33.3	6.5	8.9	14.7	100.0
5	BRAMPTON	29.9	36.8	7.2	9.8	16.3	100.0
6	BRANTFORD	31.8	35.8	7.0	9.5	15.8	100.0
7	BURLINGTON	37.1	34.0	3.0	3.0	22.9	100.0
8	CHATHAM	33.3	35.0	6.9	9.3	15.5	100.0
9	CHINGUACOUSY	16.4	43.9	8.6	11.7	19.4	100.0
10	COBOURG	51.5	25.5	5.0	6.8	11.3	100.0
11	DUNDAS	43.0	29.9	5.9	8.0	13.2	100.0
12	ETOBICOKE	20.8	41.6	8.2	11.1	18.4	100.0
13	GALT	45.2	28.8	5.6	7.5	12.7	100.0
14	GEORGETOWN	39.0	32.0	6.3	8.5	14.1	100.0
15	GUELPH	42.7	29.0	5.0	8.0	17.3	100.0
16	HAMILTON	13.6	45.4	8.9	12.1	20.0	100.0
17	KINGSTON	17.1	32.0	5.0	7.0	38.9	100.0
18	KITCH.-WATERLOO	32.0	27.0	4.0	10.0	27.0	100.0
19	LEAMINGTON	41.4	30.8	6.0	8.2	13.6	100.0
20	LINDSAY	56.4	22.9	4.5	6.1	10.1	100.0
21	LONDON	32.2	35.6	7.0	9.5	15.7	100.0
22	MARKAM	63.7	19.0	3.7	5.1	8.4	100.0
23	MIDLAND	57.7	22.2	4.4	5.9	9.8	100.0
24	MISSISSAUGA	33.9	34.7	6.8	9.3	15.3	100.0
25	NEWMARKET	70.0	15.8	3.1	4.2	7.0	100.0
26	NIAGRA FALLS	37.5	32.8	6.4	8.8	14.5	100.0
27	NORTH BAY	16.9	43.6	8.6	11.6	19.3	100.0
28	OAKVILLE	39.4	31.8	6.2	8.5	14.1	100.0
29	ORILLIA	48.6	27.0	5.3	7.2	11.9	100.0
30	OSHAWA	31.9	35.8	7.0	9.5	15.8	100.0
31	OWEN SOUND	59.5	21.3	4.2	5.7	9.4	100.0
32	PETERBOROUGH	40.3	31.3	6.1	8.4	13.9	100.0
33	PICKERING	52.9	24.7	4.9	6.6	10.9	100.0
34	PORT COLBOURNE	55.7	23.3	4.6	6.2	10.3	100.0
35	PORT ERIE	37.1	33.0	6.5	8.8	14.6	100.0
36	PRESTON	51.0	25.7	5.0	6.9	11.4	100.0
37	RICHMOND HILL	64.6	18.6	3.7	5.0	8.2	100.0
38	ST. CATHARINES	32.8	41.0	4.0	6.0	16.2	100.0
39	ST. THOMAS	38.0	32.5	6.4	8.7	14.4	100.0
40	SARINA	12.7	45.9	9.0	12.2	20.3	100.0
41	SLT. STE. MARIE	33.0	40.0	4.0	19.0	4.0	100.0
42	SCARBOROUGH	17.2	43.5	8.5	11.6	19.2	100.0
43	SIMCOE	44.7	29.0	5.7	7.7	12.8	100.0
44	STRATFORD	43.6	29.6	5.8	7.9	13.1	100.0
45	SUDBURY	52.6	24.9	4.9	6.6	11.0	100.0
46	THUNDER BAY	31.0	34.0	13.0	12.0	10.0	100.0
47	TORONTO	0.6	58.0	19.0	14.0	8.4	100.0
48	TRENTON	37.5	32.6	6.4	8.7	14.5	100.0
49	WALLACEBURG	49.9	20.3	5.2	7.0	11.6	100.0
50	WELLAND	48.4	27.1	5.3	7.2	12.0	100.0
51	WHITBY	52.5	24.9	4.9	6.7	11.0	100.0
52	WINDSOR	27.3	36.0	8.0	10.0	18.7	100.0
53	WOODSTOCK	47.9	27.4	5.4	7.3	12.1	100.0
54	YORK	1.3	51.8	10.2	13.8	22.9	100.0
55	YORK, EAST	3.4	50.7	10.0	13.5	22.4	100.0
56	YORK, NORTH	14.1	45.1	8.9	12.0	19.9	100.0
	WEIGHTED AVE.	32.6	35.4	6.9	9.4	15.6	100.0

TABLE 10. POPULATION DENSITY DISTRIBUTIONS IN NINE ONTARIO CITIES

Urbanized Area	% of Land Area in Population Density Group (PDG)					Population Densities, persons/acre in PDG				
	I	II	III	IV	V	I	II	III	IV	V
Burlington	36.2	13.3	17.1	16.1	17.3	1.71	3.82	5.34	8.98	13.59
Guelph	35.4	15.5	15.3	18.3	15.5	0.70	2.63	3.52	8.81	14.17
Kingston	37.1	16.4	17.6	13.2	15.7	4.28	7.15	11.60	18.22	25.92
Kitchener-Waterloo	37.6	17.7	17.4	14.8	12.5	1.89	4.65	8.06	11.67	15.82
St. Catharines	32.6	22.3	12.4	15.4	17.3	3.33	5.08	6.53	7.95	13.37
Sault Ste. Marie	26.8	22.7	16.0	18.3	16.2	1.34	2.88	5.32	9.02	12.59
Thunder Bay	33.8	12.3	18.6	18.5	16.8	2.45	4.02	6.75	9.97	14.68
Toronto	32.9	16.6	16.7	16.4	17.4	8.56	24.80	36.95	47.23	74.21
Windsor	31.5	19.2	16.7	16.6	16.0	1.74	4.71	7.63	11.13	19.26

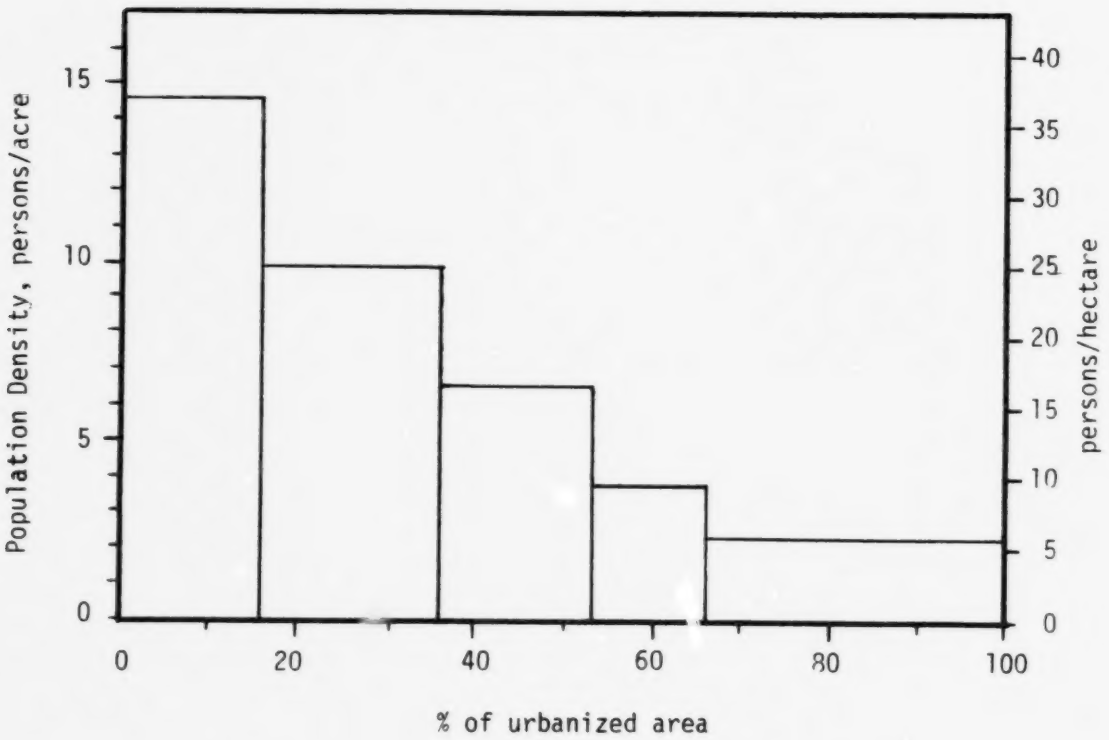


FIGURE 4. POPULATION DENSITY DISTRIBUTION OF THUNDER BAY, ONTARIO

To calibrate the overall average population density with the calculated population density, an approximate value of x_1 was found such that $PD_{x_1 - 100} = PD_{calc.}$ For example, for Thunder Bay,

$$PD = 86.4\ x^{-0.741} \tag{5}$$

and the actual average population density is 6.89 persons per acre (17.0 persons/ha).

Thus,

$$6.89 = \frac{1}{100 - x_1} \int_{x_1}^{100} 84.6\ x^{-0.741} dx \tag{6}$$

This equation is solved to find x_1. To calibrate the overall average population density with the calculated population density, for the other 47 cities, values of b were assigned based on their similarity to the nine test cities. A value of $x_1 = 2$ was used to avoid instability problems. Then, a was calculated such that the average population density, PD was

$$PD_{2 - 100} = \frac{1}{100 - 2} \int_{2}^{100} ax^b\ dx \tag{7}$$

or

$$a = \frac{98\ PD\ (1+b)}{100^{(1+b)} - 2^{(1+b)}} \tag{8}$$

Thus, the final equation for gross population density is

$$PD = ax^b \text{ with } x_1 \leq x \leq 100 \tag{9}$$

Given the equation in the form $PD = ax^b$, one can find the average population density, the proportion of the population within certain densities and so forth.

The population density function, $PD = ax^b$, is given in terms of the total urban area. Thus, it needs to be modified to integrate over only the developed portion of the urban area as shown in Figure 5. In order for the area under the two curves to be equal, one must have

$$\int_{x_1}^{100} ax^b\ dx = \int_{x_1}^{100(1-Z)} a'\ x^b\ dx \tag{10}$$

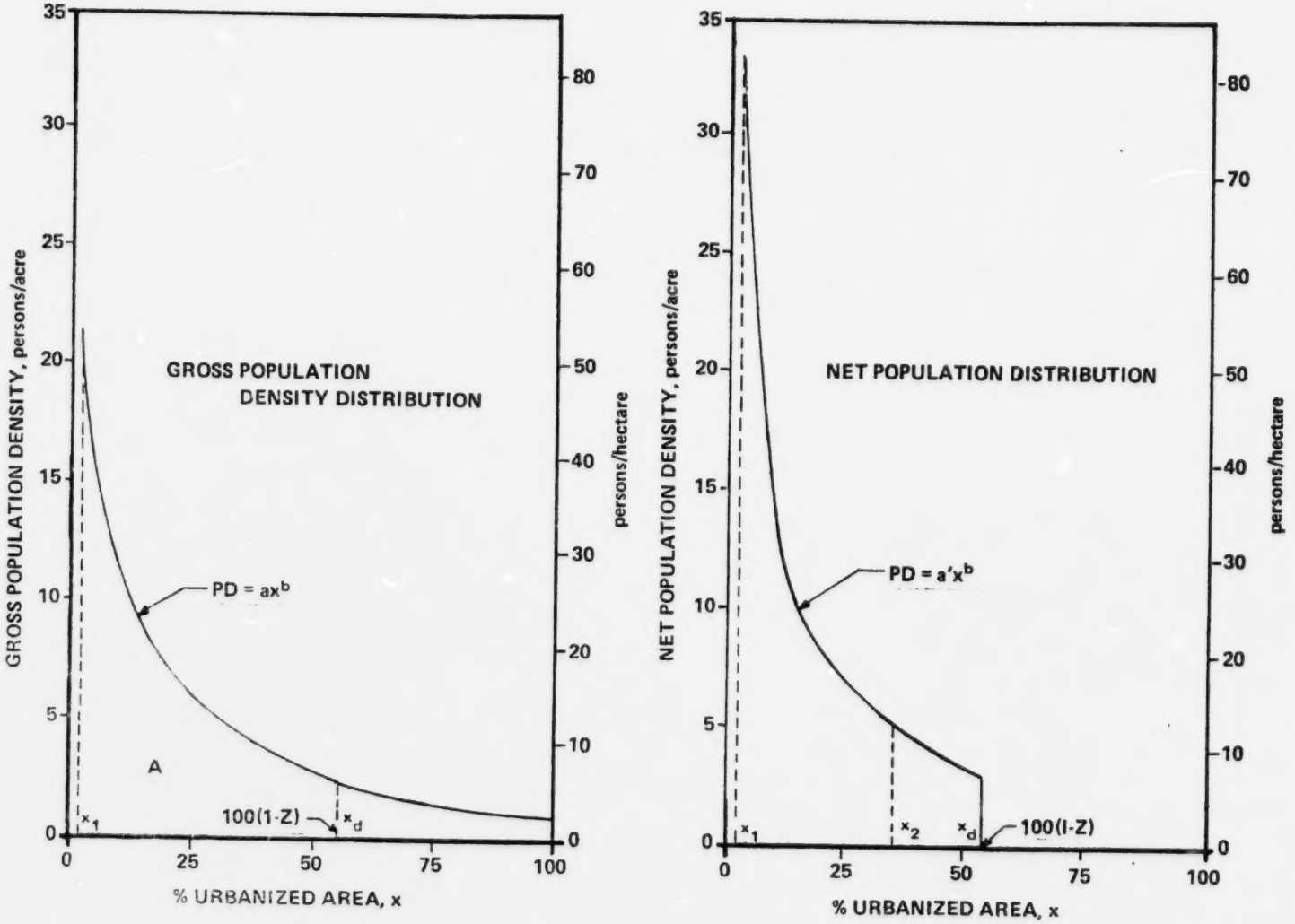


FIGURE 5. CHARACTERIZATION OF POPULATION DENSITY IN URBAN AREAS

or

$$a' = a[100^{(1+b)} - x_1^{(1+b)}]/[(100[1-Z])^{(1+b)} - x_1^{(1+b)}] \quad (11)$$

Then,

$$PD_d = a'x^b \quad (12)$$

where: PD_d = population density in developed portion of the urban area,
a' = adjusted coefficient from equation (11), and
x_1 = calibrated lower limit on percent urbanized area.

The percent of the urban area which is sewered is known for the nine test cities. Computing the corresponding PD_d for seven of the cities resulted in the values shown in Table 11. Guelph and Toronto were considered extreme values and not entered into Table 11. Based on these data, a cutoff marginal developed population density of five persons per acre (12.4 persons/ha) was used to delineate the sewered part of the urban area. Solving equation (12) for x_2 yields:

$$x_2 = \min [(5/a)^{1/b}, 100(1-Z)] \quad (13)$$

where: x_2 = percent of the urban area which is sewered.

Knowing the percent of the urban area which is undeveloped, i.e., 100(Z), the combined sewered area x_c, from the survey data, and the percent of the urban area which is sewered, x_2, then the other sewered and unsewered developed areas can be calculated as residuals. The calculation procedure is summarized below:

Sewered Areas As a Percentage of Total Urban Area

1) Undeveloped Land = $100(Z) = x_u$
2) Sewered Area = x_2
3) Combined Sewer Area = $\alpha(x_2)$, where α is the proportion of the sewered area which is combined. Values of α are taken from survey data for 49 cities. For the remaining seven cities, it is assumed that $\alpha = 0.25$.
4) Storm Sewer Area = $(1 - \alpha)x_2$
5) Unsewered Developed Area = $100 - x_u - x_2$.

TABLE 11. MARGINAL POPULATION DENSITY FOR SEWERED PORTION OF SEVEN URBAN AREAS IN CANADA

City	Marginal Sewered Population Density, PD_d (persons/acre)	(persons/ha)
Burlington	3.93	9.7
Kingston	7.28	18.0
Kitchener	4.49	11.1
St. Catharines	5.79	14.3
Sault St. Marie	4.67	11.5
Thunder Bay	6.12	15.1
Windsor	3.87	9.0
Average of 7 cities	5.16	12.8

The results of these calculations are shown in Table 12.

The population served by the various types of sewerage systems was estimated indirectly since data were unavailable. Combined sewers are installed in the older and typically more densely populated portions of the urban areas. An earlier study by Waller of combined sewers in Canada indicated that the average population density in the combined sewered portion of the two largest cities was 30.7 persons per acre [14]. The average density in the other 30 cities reporting combined sewers was 14.7 persons per acre. These results suggested that a good approximation of the population served by combined sewers would be obtained by assuming that the high density areas were combined. The next highest density is served by storm sewers and the lowest densities are unsewered. Thus, the population served by type of sewer system is calculated as shown below:

Population Served by Type of Sewerage System

1) Combined Sewers:

$$P_c = \frac{A}{100} \int_{x_1}^{x_c} a' x^b \, dx \qquad (14)$$

TABLE 12. LAND USE BY TYPE OF SEWERAGE SYSTEM

NO	ORGANIZED AREA	LAND USE PERCENTAGES				
		UND	COMB	STORM	UNSEW	TOTAL
1	AJAX	47.5	5.2	15.5	31.9	100.0
2	AURORA	76.5	0.0	8.0	15.5	100.0
3	BARRIE	51.3	0.0	16.5	32.6	100.0
4	BELLEVILLE	30.5	11.5	22.3	29.6	100.0
5	BRAMPTON	29.9	0.0	59.0	11.0	100.0
6	BRANTFORD	31.8	0.0	54.1	14.1	100.0
7	BURLINGTON	37.1	0.0	36.2	26.7	100.0
8	CHATHAM	33.3	18.7	31.7	16.3	100.0
9	CHINGUACOUSY	18.4	0.0	78.6	3.0	100.0
10	COBOURG	51.3	0.0	18.7	29.0	100.0
11	DUNDAS	43.0	0.0	42.0	34.0	100.0
12	ETOBICOKE	30.8	0.0	56.1	13.0	100.0
13	GALT	46.2	0.0	21.8	32.0	100.0
14	GEORGETOWN	34.0	0.0	25.2	35.8	100.0
15	GUELPH	42.7	0.0	26.2	31.1	100.0
16	HAMILTON	17.8	63.7	28.7	0.0	100.0
17	KINGSTON	17.1	22.4	60.5	0.0	100.0
18	KITCH.-WATERLOO	32.0	0.0	41.9	26.1	100.0
19	LEAMINGTON	41.4	7.0	17.9	34.8	100.0
20	LINESAY	58.4	3.2	10.5	27.1	100.0
21	LONDON	32.3	9.6	27.5	31.1	100.0
22	MARKAM	54.7	3.5	19.1	22.6	100.0
23	MIDLAND	27.7	14.3	1.9	26.4	100.0
24	MISSISSAUGA	35.3	0.3	40.3	23.6	100.0
25	NEWMARKET	70.0	0.0	11.0	19.0	100.0
26	NIAGRA FALLS	37.3	30.6	2.3	29.6	100.0
27	NORTH BAY	19.3	3.9	74.1	3.1	100.0
28	OAKVILLE	30.4	0.0	39.9	29.7	100.0
29	ORILLIA	42.5	0.2	26.1	31.3	100.0
30	OSHAWA	31.9	0.2	53.9	14.2	100.0
31	OWEN SOUND	36.9	7.6	7.6	25.4	100.0
32	PETERBOROUGH	40.3	0.3	24.4	35.4	100.0
33	PICKERING	32.3	0.2	18.3	29.1	100.0
34	PORT COLBOURNE	55.7	0.0	16.8	27.5	100.0
35	PORT ERIE	37.1	7.1	19.7	36.5	100.0
36	PRESTON	31.0	0.0	18.4	50.1	100.0
37	RICHMOND HILL	44.5	0.0	13.1	22.4	100.0
38	ST. CATHARINES	30.8	27.9	28.0	13.3	100.0
39	ST. THOMAS	38.0	15.2	5.4	36.2	100.0
40	SARNIA	16.7	22.7	54.6	0.0	100.0
41	SLT. STE. MARIE	33.0	0.0	32.2	34.8	100.0
42	SCARBOROUGH	17.2	15.4	61.7	5.7	100.0
43	SIMCOE	44.7	5.5	16.5	33.2	100.0
44	STRATFORD	43.5	0.0	22.5	33.9	100.0
45	SUDBURY	52.1	0.0	19.7	27.3	100.0
46	THUNDER BAY	31.0	11.7	35.1	22.2	100.0
47	TORONTO	0.6	74.5	24.9	0.0	100.0
48	TRENTON	27.5	0.0	25.1	36.4	100.0
49	WALLACEBURG	49.4	7.2	12.0	31.7	100.0
50	WELLAND	48.4	9.1	11.1	31.4	100.0
51	WHITBY	52.2	0.0	18.2	29.3	100.0
52	WINDSOR	27.1	14.1	31.4	27.2	100.0
53	WOODSTOCK	47.9	0.0	20.4	31.7	100.0
54	YORK	1.3	82.9	15.9	0.0	100.0
55	YORK.EAST	3.4	90.3	6.3	0.0	100.0
56	YORK.NORTH	14.1	0.0	85.9	0.0	100.0
	WEIGHTED AVE.	32.6	12.7	35.1	19.5	100.0

2) Storm Sewers:

$$P_s = \frac{A}{100} \int_{x_c}^{x_2} a' \, x^b \, dx \qquad (15)$$

3) Unsewered (no storm or combined sewers):

$$P_u = \frac{A}{100} \int_{x_2}^{x_d} a' \, x^b \, dx \qquad (16)$$

where: A = total urban area in acres

The resulting population by type of sewerage system is shown in Table 13. Lastly, the population densities by type of sewer system are shown in Table 14.

3.4 List of Variables

a	constant
a'	adjusted coefficient
α	proportion of sewered area which is combined
b	constant
P_c	population served by combined sewer system (persons)
P_s	population served by storm sewer system (persons)
P_u	unsewered population
PD	gross population density (persons per acre)
$\overline{PD}$	average population density (persons per acre)
PD_{calc}	calculated average population density (persons per acre)
$PD_{x_1 - x_2}$	average population density in interval from x_1 to x_2 (persons per acre)
PD_d	population density in developed portion of urban area (persons per acre)
r	correlation coefficient
x	percent of urban area
x_1	calibrated lower limit on x such that average PD corresponds to the integrated average PD
x_2	calibrated upper limit on x such that average PD corresponds to the integrated average PD and percent of urban area which is sewered

TABLE 13. POPULATION SERVED BY TYPE OF SEWERAGE SYSTEM

NO	ORGANIZED AREA	POPULATION SERVED (1000 PERSONS)			
		COMB	STORM	UNSEW	TOTAL
1	AJAX	4.4	5.2	2.9	12.5
2	AURORA	0.0	7.3	4.0	11.3
3	BARRIE	0.0	20.9	6.8	27.7
4	BELLEVILLE	15.6	11.8	7.7	35.1
5	BRAMPTON	0.0	37.5	3.7	41.2
6	BRANTFORD	0.0	39.2	7.7	53.9
7	BURLINGTON	0.0	63.5	17.1	80.6
8	CHATHAM	16.4	13.2	5.1	35.3
9	CHINGUACOUSY	0.0	21.7	0.4	22.1
10	COBOURG	0.0	8.8	2.8	11.7
11	DUNDAS	0.0	13.8	3.8	17.6
12	ETOBICOKE	0.0	252.2	20.5	272.7
13	GALT	0.0	30.2	8.7	38.9
14	GEORGETOWN	0.0	13.5	3.5	17.0
15	GUELPH	0.0	44.2	12.4	56.6
16	HAMILTON	272.8	33.3	0.0	305.5
17	KINGSTON	53.6	30.4	0.0	53.0
18	KITCH.-WATERLOO	0.0	120.2	27.7	147.9
19	LEAMINGTON	4.1	4.2	2.2	10.4
20	LINDSAY	0.0	9.4	3.3	12.7
21	LONDON	87.7	89.5	43.3	220.5
22	MARKAM	3.5	8.0	4.7	16.2
23	MIDLAND	7.7	0.3	2.9	11.0
24	MISSISSAUGA	0.0	120.8	29.3	150.3
25	NEWMARKET	0.0	12.5	5.0	17.5
26	NIAGRA FALLS	47.0	1.5	14.3	62.7
27	NORTH BAY	2.8	20.2	0.5	23.5
28	OAKVILLE	0.7	41.7	13.0	54.7
29	ORILLIA	0.0	18.4	5.7	24.0
30	OSHAWA	0.0	60.5	11.0	71.5
31	OWEN SOUND	0.7	4.1	5.0	18.5
32	PETERBOROUGH	0.0	45.7	12.1	57.8
33	PICKERING	0.0	14.3	4.8	19.1
34	PORT COLBORNE	0.0	13.8	4.7	18.0
35	PORT ERIE	4.8	4.5	2.7	11.9
36	PRESTON	0.0	12.7	4.1	16.7
37	RICHMOND HILL	0.0	18.6	7.7	26.3
38	ST. CATHARINES	58.2	34.7	14.3	107.2
39	ST. THOMAS	18.3	1.7	5.2	25.2
40	SARNIA	30.5	26.5	0.0	57.0
41	SLT. STE. MARIE	0.0	52.7	17.3	70.0
42	SCARBOROUGH	144.6	176.6	9.9	331.2
43	SIMCOE	4.0	4.4	2.4	10.8
44	STRATFORD	0.0	19.1	5.4	24.5
45	SUDBURY	0.2	32.4	28.1	60.5
46	THUNDER BAY	36.4	45.0	15.8	97.2
47	TORONTO	627.9	85.2	0.0	713.0
48	TRENTON	0.0	11.7	2.9	14.6
49	WALLACEBURG	4.3	3.1	2.6	10.0
50	WELLAND	22.3	9.8	9.5	41.7
51	WHITBY	0.0	10.9	4.2	15.1
52	WINDSOR	94.4	74.4	31.5	200.3
53	WOODSTOCK	0.0	20.1	0.1	20.2
54	YORK	134.5	8.9	0.0	147.3
55	YORK, EAST	38.7	16.3	0.0	104.8
56	YORK, NORTH	0.0	60.1	0.0	304.1
	TOTAL	1773.	2481.	468.	4725.

TABLE 14. POPULATION DENSITY BY TYPE OF SEWERAGE SYSTEM

NO	URBANIZED AREA	POPULATION DENSITY (PERSONS/ACRE)			
		COMB	STORM	UNSEW	AVE.
1	AJAX	22.62	11.23	3.13	8.34
2	AURORA	0.0	11.23	3.74	6.74
3	BARRIE	0.0	15.73	3.21	8.07
4	BELLEVILLE	22.84	8.83	4.41	9.32
5	BRAMPTON	0.0	10.24	5.74	10.13
6	BRANTFORD	0.0	10.27	5.71	9.29
7	BURLINGTON	0.0	12.24	4.65	9.28
8	CHATHAM	15.04	8.01	5.70	8.70
9	CHINGUACOUSY	0.0	12.24	5.23	12.71
10	COBOURG	0.0	15.78	3.20	8.05
11	DUNDAS	0.0	10.91	3.18	8.71
12	ETOBICOKE	0.0	12.25	5.13	11.09
13	GALT	0.0	10.63	3.14	8.59
14	GEORGETOWN	0.0	17.45	3.18	9.04
15	GUELPH	0.0	14.98	3.51	8.74
16	HAMILTON	15.85	6.04	0.0	13.54
17	KINGSTON	22.48	8.85	0.0	12.53
18	KITCH.-WATERLOO	0.0	12.54	4.01	9.85
19	LEAMINGTON	13.73	11.56	3.18	8.55
20	LINDSAY	0.0	15.11	3.24	7.73
21	LONDON	21.83	9.57	4.19	9.83
22	MARKAM	17.04	13.01	3.35	7.31
23	MIDLAND	15.87	8.73	3.26	7.65
24	MISSISSAUGA	0.0	12.64	4.87	9.63
25	NEWMARKET	0.0	13.01	3.31	8.99
26	NIAGRA FALLS	14.15	8.04	4.40	9.23
27	NORTH BAY	32.07	12.06	5.20	12.59
28	OAKVILLE	0.0	13.50	4.79	9.04
29	ORILLIA	0.0	16.17	3.13	8.25
30	OSHAWA	0.0	10.67	5.71	9.88
31	OWEN SOUND	20.42	8.62	3.28	7.54
32	PETERBOROUGH	0.0	17.28	3.18	8.95
33	PICKERING	0.0	15.53	3.21	7.95
34	PORT COLBORNE	0.0	15.21	3.24	7.77
35	PORT ERIE	36.59	11.41	3.19	9.27
36	PRESTON	0.0	15.85	3.20	8.04
37	RICHMOND HILL	0.0	13.41	3.37	7.29
38	ST. CATHARINES	14.32	7.59	5.72	9.77
39	ST. THOMAS	21.29	6.48	3.19	9.19
40	SARINA	28.55	9.74	0.0	13.93
41	SLT. STE. MARIE	0.0	12.83	4.05	8.24
42	SCARBOROUGH	29.36	8.98	5.25	12.52
43	SIMCOE	31.52	11.74	3.13	8.59
44	STRATFORD	0.0	14.94	3.18	8.65
45	SUDBURY	0.0	13.09	4.25	7.87
46	THUNDER BAY	22.06	9.09	5.04	9.99
47	TORONTO	35.05	14.30	0.0	29.37
48	TRENTON	0.0	17.65	3.19	9.25
49	WALLACEBURG	26.36	9.90	3.19	8.19
50	WELLAND	25.12	8.90	3.19	9.27
51	WHITBY	0.0	15.64	3.21	7.94
52	WINDSOR	25.54	9.09	4.44	10.50
53	WOODSTOCK	0.0	16.27	3.19	8.31
54	YORK	29.11	9.50	0.0	26.04
55	YORK-EAST	27.61	8.80	0.0	20.65
56	YORK-NORTH	0.0	13.42	0.0	13.42
	WEIGHTED AVE.	24.39	11.83	4.10	11.99

x_c	percent of urban area served by combined sewers
x_d	percent of urban area which is developed
x_u	percent of urban area which is undeveloped
Z	undeveloped portion of urban area

4. RUNOFF AND POLLUTANT LOAD ESTIMATES

The purpose of this Section is to estimate the quantity and quality of urban runoff from the 56 urban areas. The first part provides some background information regarding models which are used to assist in making decisions. Then, precipitation patterns are analyzed to form a basis for predicting the quantity of urban runoff. The relevant water quality parameters are discussed and the results of numerous attempts to estimate runoff quality are presented. Finally, a pollutant load prediction equation is developed which provides the basis for assessing pollutant loads. A summary of the methodology is presented elsewhere [62, 63].

4.1 Modelling of Urban Runoff

4.1.1 Computer models

The overall goal of urban runoff modelling is to aid in decision-making for the abatement of water quantity and quality problems. Thus, computer models do not provide "solutions" to problems. Rather, they serve as useful tools to those charged with devising such solutions. Within this context, subobjectives of the modelling process may be identified: planning, design, and operation. Models for the latter category are generally site-specific [16, 17] and were not considered during this study. However, numerous models are available for planning and design purposes, e.g. the U.S. Army Corps of Engineers' STORM and the U.S. EPA Storm Water Management Model (SWMM). However, they are not unique; several other urban runoff models are capable of similar tasks [18, 19, 20].

Computer models are merely mathematical abstractions of the physics of the urban runoff processes and do not necessarily produce accurate or even logical predictions without extensive calibration/verification data. These are in addition to data required as model input, such as topography, land use, rainfall, antecedent conditions, description of drainage system and storage-treatment facilities.

Among the principal 1965 findings of the ASCE Council on Urban Water Resources [21] was the serious need for field data on rainfall-runoff-quality for several catchments. Unfortunately, in spite of efforts

by federal agencies in the United States and Canada, this need still exists, especially in the area of data for calibration/verification of urban hydrology models. For instance, few new discharge data have been acquired on sewered catchments, using flumes, weirs, or other accurate devices rather than conversion of stage gauge readings for determination of flow rates [22]. The state-of-the-art in computation and simulation tools has, thus, outstripped its available calibration/verification data base. However, current analytical techniques will necessarily rely on computer models, especially for planning and design purposes. Hence, the ultimate goal of acquisition of salient field data remains worthwhile and necessary. Throughout this section, gaps in available data for input and calibration/verification will be apparent. But the useful analyses which can still be performed without these data should also be clear.

The modelling procedures developed for the assessment will be discussed in detail. Two levels of sophistication are considered: use of STORM for the development of the parameters used in the assessment methodology described in Section 6, and use of a very simple runoff prediction technique for the 56 urban areas of the Ontario assessment itself.

4.1.2 Runoff analysis using STORM

The Storage, Treatment, Overflow and Runoff Model (STORM) was developed by Water Resources Engineers, Inc., (WRE) for the Hydrologic Engineering Center (HEC) of the U.S. Army Corps of Engineers [11, 23]. The model was designed for planning purposes, i.e., for long-term simulation of many storm events using an hourly time step. For instance, the model has been used to simulate runoff quality and simple storage-treatment options for a 63-year record of hourly rainfalls in San Francisco.

When STORM is used for planning, the primary objective is to illustrate the effect of various storage-treatment combinations at the downstream end of an entire urban catchment that provide given levels of control. "Level of control" may refer to percent of runoff captured, percent BOD or other pollutant removed, number of overflows per year, quantity of overflow per year, etc. Use of the model for this primary objective is described in detail in Section 6 of this report, including a

discussion of the methodology employed. Thus, the use of STORM in this study is deferred to that section.

4.2 Runoff Prediction for Ontario Assessment

4.2.1 The hydrologic cycle

The hydrologic cycle may be divided into three principal phases: 1) precipitation, 2) evaporation, and 3) surface and groundwater runoff. The hydrologic cycle has neither beginning nor end, as water evaporates to the atmosphere from land and water surfaces. The evaporated moisture eventually precipitates back to the earth where it may be intercepted or transpired by plants, may become surface runoff, or may infiltrate into the ground. Once in the ground, water may be stored as soil moisture and evapotranspired, or percolate to deeper zones to become part of groundwater flow. Surface and groundwater flow from the land eventually reaches streams, lakes, or oceans from which water evaporates to complete the cycle.

4.2.2 Form of the equation

Techniques for prediction of runoff quantities vary from very simple methods of the rational method type to sophisticated models of the nature of SWMM. The technique used in STORM is relatively simple, relying on weighted average runoff coefficients and a simple loss function to predict hourly runoff volumes. Nonetheless, because of the nature of the continuous simulation involved, it is at a considerably higher level, and therefore more complex, than earlier, desk-top techniques.

Due to the complexities and data requirements of STORM, it was not possible to run the model on all cities of the assessment, or even a majority. Rather it was run only on four test cities as discussed in Section 6. However, in its limited application, useful information was learned regarding formulation of a simple runoff prediction method for application to all the cities of the assessment.

Runoff is a function of meteorologic, hydrologic, topographic, and demographic factors. On an annual basis, many of the factors may be considered constant, so that runoff is predicted on the basis of differences between areas rather than reflecting seasonal variations within a year. Hence, the prime meteorologic and hyrologic factor is

annual precipitation, and other factors are incorporated into a conversion to annual runoff.

These considerations lead directly to the use of a simple runoff coefficient method in which runoff is merely a fraction of rainfall. This approach has been used successfully by Miller and Viessman [24] for runoff prediction on an individual storm basis in urban areas. This equation was:

$$AR = 1.165\ (I - 0.17)\ (P - I_a) \qquad (17)$$

where: AR = runoff, inches;
I = fraction imperviousness;
P = precipitation, inches; and
I_a = initial abstraction, inches.

The recommended value of I_a, which accounts for initial losses such as depression storage, interception, etc., was between 0.10 and 0.15 in. (0.25 and 0.38 cm), and the equation was deemed valid for a range of imperviousness between 35 and 80 percent. Extrapolation for use on an annual average basis, however, may be questionable, particularly in the matter of how much water should be abstracted out of the cycle on an annual basis. Hence, an equation will be used that is similar in form to equation (17), but which is consistent with the STORM simulation runs, described in Section 6, on which the overall assessment was based.

STORM computes a runoff coefficient, CR, weighted between pervious and impervious areas by:

$$CR = 0.15\ (1 - I) + 0.90\ I$$
$$= 0.15 + 0.75\ I \qquad (18)$$

where I is fraction imperviousness and the coefficients 0.15 and 0.90 are the default values used in STORM for runoff coefficients from pervious and impervious areas, respectively. Note that in both equations (17) and (18) the effect of demographic factors (e.g., land use, population density) is incorporated into the imperviousness, I.

Imperviousness was estimated for the nine cities discussed in Section 4 using the same maps used to estimate land use. The average residence was assumed to have an impervious area of 1,500 ft^2 (139 m^2)

and the average street width was taken to be 34 ft (10.4 m) regardless of land use. These assumptions were necessary due to the large scale of the aerial photos. Structures on institutional, industrial, and commercial lands were usually large enough to be measured. For each city, the procedure was to choose three or four representative areas for each land use and to determine a figure for percent imperviousness from these samples. The determination of curb length for each land use also required the use of aerial photographs. Again, representative areas of each land use were chosen. Street lengths were measured, and along with the assumption that curb length equals twice the street length, figures for curb length per acre were determined. The results of these studies are shown in Table 15.

The American Public Works Association [3], Graham et al [25], and Stankowski [26] have developed equations to predict imperviousness as a function of population density. The imperviousness is to be estimated for the developed portion of the urbanized area only. The weighted average imperviousness and population density were calculated for the nine Ontario cities. These results are plotted on Figure 6, along with the three estimating curves. Also, a tabulation was made of the imperviousness due to streets alone for various block sizes as shown in Table 16. These results are also plotted on Figure 6. A comparison of these various plots and the actual data indicates that the New Jersey [26] equation provides a suitable predictive equation with population density defined as developed population density. Thus, the equation used to estimate imperviousness is

$$I = 0.96\ PD_d^{(0.573-0.0391\ \log_{10} PD_d)} \tag{19}$$

where: I = imperviousness in percent, and

PD_d = population density in developed portion of the urbanized area, persons per acre.

The simplified equation for estimating annual runoff (AR) is now

$$AR = (0.15 + 0.75I)P \tag{20}$$

TABLE 15. IMPERVIOUSNESS AND CURB LENGTH DENSITY BY TYPE OF LAND USE IN NINE ONTARIO CITIES

Urbanized Area	Imperviousness, I* or Curb Length Density, G_L**	Residential	Commercial	Industrial	Institutional	Open
Burlington	I	32	89	11	37	3
	G_L	365 (275)	178 (134)	136 (102)	125 (94)	57 (39)
Guelph	I	30	89	43	36	1
	G_L	339 (255)	254 (191)	121 (91)	153 (115)	32 (24)
Kingston	I	27	87	20	17	3
	G_L	332 (250)	314 (236)	82 (62)	56 (42)	44 (33)
Kitchener-Waterloo	I	29	82	52	36	8
	G_L	355 (267)	216 (163)	142 (107)	113 (85)	35 (26)
St. Catharines	I	27	90	42	38	4
	G_L	331 (249)	238 (179)	146 (110)	150 (113)	60 (45)
Sault Ste. Marie	I	22	74	57	22	3
	G_L	353 (266)	461 (347)	150 (113)	244 (184)	44 (33)
Thunder Bay	I	29	78	44	32	2
	G_L	388 (292)	331 (249)	58 (44)	216 (163)	41 (31)
Toronto	I	44	52	44	31	14
	G_L	355 (267)	362 (273)	261 (197)	307 (231)	345 (260)
Windsor	I	31	88	48	18	5
	G_L	382 (288)	337 (254)	121 (91)	133 (100)	71 (53)
Average	I	30	81	40	30	5
	G_L	356 (268)	299 (225)	135 (102)	166 (125)	81 (61)

* % measured in percent of total

** ft per acre (metres per hectare).

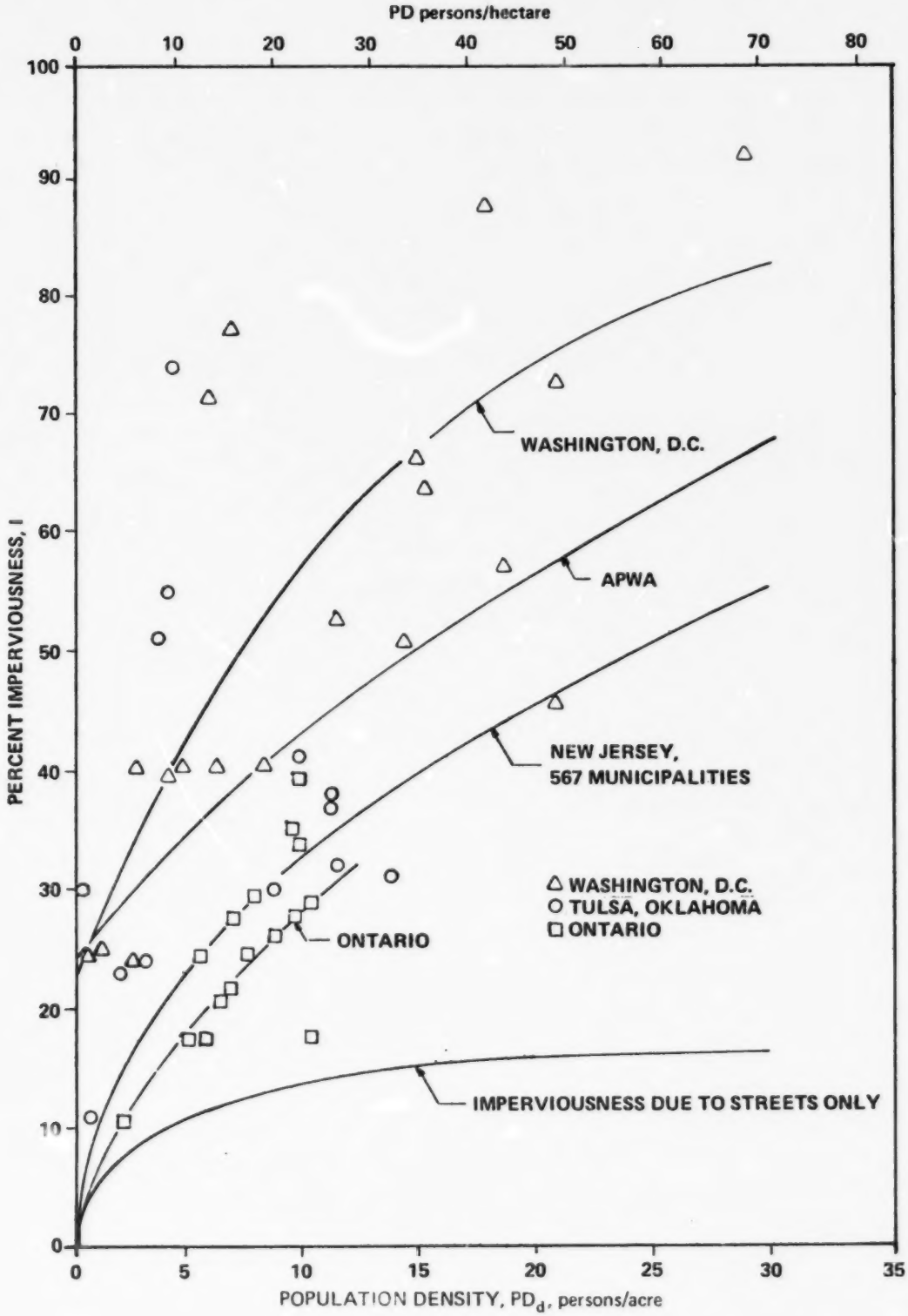


FIGURE 6. IMPERVIOUSNESS AS A FUNCTION OF POPULATION DENSITY

TABLE 16. EFFECT OF URBAN BLOCK SIZE ON CURB LENGTH DENSITY AND IMPERVIOUSNESS DUE TO STREETS

Block Size ft x ft (m x m)	Area, ac (ha)	Curb Length Density ft/ac (m/ha)	Imperviousness due to Street*
660 x 330 (201 x 101)	5 (2.02)	392.0 (298.0)	0.150
1,320 x 660 (402 x 201)	20 (8.09)	198.0 (148.0)	0.077
2,640 x 1,320 (805 x 402)	80 (32.40)	99.0 (74.6)	0.039
5,280 x 2,640 (1,609 x 807)	320 (130.00)	49.5 (37.3)	0.019

* Assume 34 ft (10.4 m) wide street.

where: AR = annual runoff, inches,

I = fraction imperviousness from equation (19), and

P = annual precipitation, inches.

A comparison of STORM simulated runoff versus calculated runoff using equation (20) is shown in Table 17. The average difference is about 0.5 inches (1.27 cm) per year. A similar comparison in the U.S. assessment indicated a difference of 0.3 inches (0.76 cm) per year. Thus, a correction factor was added to equation (20) to reflect this difference. The final equation is

$$AR = (0.15 + 0.75I) P - 0.5 \qquad (21)$$

Based on equation (21), wet-weather flow estimates were made for the 56 urban areas for the combined, storm, and unsewered areas. The results are shown in Table 18.

4.2.3 Dry-weather flow prediction

Dry-weather flow is predicted, based on actual flow data for the test cities, indicating an average flow of 108 U.S. gallons per person-day (410 litres per person-day). Upon multiplication by population density and conversion to appropriate units:

TABLE 17. COMPARISON OF SIMULATED AND CALCULATED RUNOFF FOR FOUR TEST CITIES

City	Annual[a] Precipitation in/yr (cm/yr)	Runoff[b] Coefficient	Runoff: in/yr (cm/yr) STORM[c]	Calculated[d]	Difference
Burlington	32.4 (82.3)	0.344	10.62 (26.97)	11.15 (28.31)	0.53 (1.34)
Kingston	37.8 (96.0)	0.306	11.11 (28.22)	11.57 (29.38)	0.46 (1.16)
St. Catharines	32.4 (82.3)	0.372	11.41 (28.98)	12.05 (30.61)	0.64 (1.63)
Sault Ste. Marie	36.7 (93.2)	0.413	14.54 (36.93)	15.16 (38.50)	0.62 (1.57)

[a]See Section 6.4.

[b]Equation (18) and Table 15.

[c]Assumed depression storage = 0.01 inch, runoff coefficient from equation (18); see Section 6.4.

[d]Equation (20)

$$DWF = 1.45\ PD_d \qquad (22)$$

where: DWF = annual dry-weather flow, inches per year, and

PD_d = developed population density, persons per acre.

Results of these runoff calculations are shown in Table 19. Dry-weather flow is generated for entry into a sanitary sewer for storm or unsewered areas.

Dry-weather flow and wet-weather flow for the developed portions of an urban area with a precipitation of 15, 30, or 45 inches per year are shown in Figure 7. Note that dry-weather flow predominates at higher population densities which have historically prevailed in cities. However, with the trend towards lower density urban living, wet-weather flows take on greater relative importance. Indeed, they are larger than dry-weather flows at the lower population densities.

TABLE 18. ANNUAL WET-WEATHER RUNOFF FOR COMBINED, STORM, AND UNSEWERED AREAS

NO	URBANIZED AREA	ANNUAL PRECIP IN/YR	WET-WEATHER FLOW (INCHES PER YEAR) COMB	STORM	UNSEW	AVER
1	AJAX	33	18.1	13.3	9.0	11.1
2	AURORA	31	0.0	12.5	8.8	10.1
3	BARRIE	32	0.0	14.1	8.7	10.8
4	BELLEVILLE	34	17.0	12.5	10.1	12.2
5	BRAMPTON	31	0.0	12.1	9.9	11.8
6	BRANTFORD	32	0.0	12.5	10.2	12.1
7	BURLINGTON	32	0.0	13.2	9.6	11.9
8	CHATHAM	30	13.3	10.6	9.6	11.1
9	CHINGUACOUSY	31	0.0	12.8	9.7	12.7
10	COBOURG	34	0.0	15.1	9.3	11.5
11	DUNDAS	32	0.0	14.5	8.7	11.0
12	ETOBICOKE	31	0.0	12.8	9.6	12.3
13	GALT	33	0.0	14.9	9.0	11.3
14	GEORGETOWN	32	0.0	14.6	8.7	11.1
15	GUELPH	33	0.0	14.3	9.2	11.5
16	HAMILTON	32	14.2	10.4	0.0	13.3
17	KINGSTON	35	17.5	12.9	0.0	14.1
18	KITCH.-WATERLOO	34	0.0	14.1	10.4	12.7
19	LEAMINGTON	30	17.2	11.9	8.1	10.2
20	LINDSAY	33	0.0	14.4	9.0	11.0
21	LONDON	37	20.2	14.1	10.9	13.4
22	MARKAM	31	14.1	12.8	8.5	10.2
23	MIDLAND	38	16.9	12.7	10.5	12.7
24	MISSISSAUGA	31	0.0	13.7	9.5	12.4
25	NEWMARKET	31	0.0	12.8	8.6	10.2
26	NIAGRA FALLS	33	14.1	10.8	9.8	11.9
27	NORTH BAY	35	19.7	14.2	11.0	14.3
28	OAKVILLE	31	0.0	13.0	9.2	11.1
29	ORILLIA	36	0.0	18.1	9.8	12.5
30	OSHAWA	34	0.0	13.4	10.9	12.9
31	OWEN SOUND	35	16.9	12.9	9.6	11.6
32	PETERBOROUGH	32	0.0	14.6	8.7	11.1
33	PICKERING	31	0.0	13.6	8.4	10.4
34	PORT COLBOURNE	34	0.0	14.9	9.3	11.4
35	PORT ERIE	34	20.1	13.5	9.3	11.7
36	PRESTON	34	0.0	15.1	9.3	11.5
37	RICHMOND HILL	31	0.0	13.1	8.5	10.2
38	ST. CATHARINES	32	13.9	11.2	10.2	11.9
39	ST. THOMAS	35	17.2	11.7	9.5	12.1
40	SARINA	34	18.4	12.4	0.0	14.0
41	SLT. STE. MARIE	37	0.0	15.4	10.8	13.0
42	SCARBOROUGH	31	16.9	11.4	9.7	12.3
43	SIMCOE	35	19.6	14.1	9.5	11.9
44	STRATFORD	38	0.0	17.2	10.4	13.1
45	SUDBURY	32	0.0	13.3	9.4	11.0
46	THUNDER BAY	28	13.8	10.3	8.6	10.3
47	TORONTO	31	18.0	13.2	0.0	16.8
48	TRENTON	33	0.0	15.2	9.0	11.5
49	WALLACEBURG	30	15.7	11.3	8.1	10.0
50	WELLAND	34	17.6	12.5	9.2	11.4
51	WHITBY	34	0.0	15.0	9.3	11.5
52	WINDSOR	30	15.6	11.0	8.9	11.1
53	WOODSTOCK	34	0.0	15.2	9.2	11.6
54	YORK	31	16.8	11.7	0.0	16.0
55	YORK, EAST	31	16.5	11.3	0.0	14.6
56	YORK, NORTH	31	0.0	13.0	0.0	13.0
	WEIGHTED AVE.	32.75	16.2	12.8	9.5	12.5

TABLE 19. ANNUAL DRY-WEATHER RUNOFF FOR COMBINED, STORM, AND UNSEWERED AREAS

NO	URBANIZED AREA	ANNL A PRECP IN/YR	DRY WEATHER FLOW (INCHES PER YEAR) COMB	STORM	UNSEW	AVER
1	AJAX	33	39.8	16.0	4.3	11.2
2	AURORA	31	0.0	16.1	5.0	9.1
3	BARRIE	32	0.0	21.1	4.3	10.8
4	BELLEVILLE	34	30.7	11.9	5.9	12.5
5	BRAMPTON	31	0.0	14.7	7.7	13.6
6	BRANTFORD	32	0.0	14.7	7.7	13.3
7	BURLINGTON	32	0.0	17.1	6.2	12.5
8	CHATHAM	30	21.6	10.8	7.7	13.0
9	CHINGUACOUSY	31	0.0	17.6	7.7	17.1
10	COBOURG	34	0.0	21.2	4.3	10.8
11	DUNDAS	32	0.0	22.7	4.3	11.7
12	ETOBICOKE	31	0.0	17.4	6.9	15.7
13	GALT	32	0.0	22.3	4.3	11.5
14	GEORGETOWN	32	0.0	23.5	4.3	12.2
15	GUELPH	32	0.0	20.1	4.7	11.7
16	HAMILTON	32	21.4	8.2	0.0	18.3
17	KINGSTON	35	30.2	11.9	0.0	16.8
18	KITCH.-WATERLOO	34	0.0	17.4	6.5	13.2
19	LEAMINGTON	30	45.4	15.6	4.3	11.9
20	LINDSAY	33	0.0	20.3	4.4	10.4
21	LONDON	37	38.8	13.3	5.6	13.2
22	MARKAM	31	23.0	17.5	4.5	9.8
23	MIDLAND	28	21.3	8.6	4.4	10.3
24	MISSISSAUGA	31	0.0	17.0	6.6	12.0
25	NEWMARKET	33	0.0	17.5	4.7	9.4
26	NIAGRA FALLS	33	19.0	8.2	5.9	12.4
27	NORTH BAY	35	43.1	16.2	7.1	16.9
28	OAKVILLE	31	0.0	18.1	5.9	12.1
29	ORILLIA	36	0.0	21.7	8.3	11.3
30	OSHAWA	34	0.0	14.7	7.7	13.3
31	OWEN SOUND	35	27.4	12.0	4.4	10.1
32	PETERBOROUGH	32	0.0	23.2	4.3	12.0
33	PICKERING	31	0.0	20.9	4.3	10.7
34	PORT COLBOURNE	34	0.0	20.4	4.8	10.4
35	PORT ERIE	34	49.2	15.3	4.3	12.5
36	PRESTON	34	0.0	21.3	4.3	10.9
37	RICHMOND HILL	31	0.0	18.7	4.5	9.8
38	ST. CATHARINES	32	20.1	10.2	7.7	13.1
39	ST. THOMAS	35	28.6	8.7	4.3	12.3
40	SARINA	34	38.5	11.8	0.0	18.7
41	SLT. STE. MARIE	37	0.0	17.3	5.4	11.1
42	SCARBOROUGH	31	39.5	12.1	7.1	16.8
43	SIMCOE	33	42.4	15.8	4.3	11.5
44	STRATFORD	38	0.0	22.6	4.3	11.6
45	SUDBURY	32	0.0	17.6	5.7	10.7
46	THUNDER BAY	28	29.7	12.2	5.8	13.4
47	TORONTO	31	47.1	19.2	0.0	40.1
48	TRENTON	33	0.0	23.7	4.3	12.4
49	WALLACEBURG	30	35.4	13.3	4.3	11.0
50	WELLAND	34	33.8	12.0	4.3	11.1
51	WHITBY	34	0.0	21.0	4.3	10.7
52	WINDSOR	30	34.3	12.1	6.0	14.1
53	WOODSTOCK	34	0.0	21.9	4.3	11.2
54	YORK	31	39.1	13.3	0.0	35.0
55	YORK, EAST	31	37.1	11.8	0.0	27.8
56	YORK, NORTH	31	0.0	18.0	0.0	18.0
	WEIGHTED AVE.	32.75	35.4	15.9	5.5	16.1

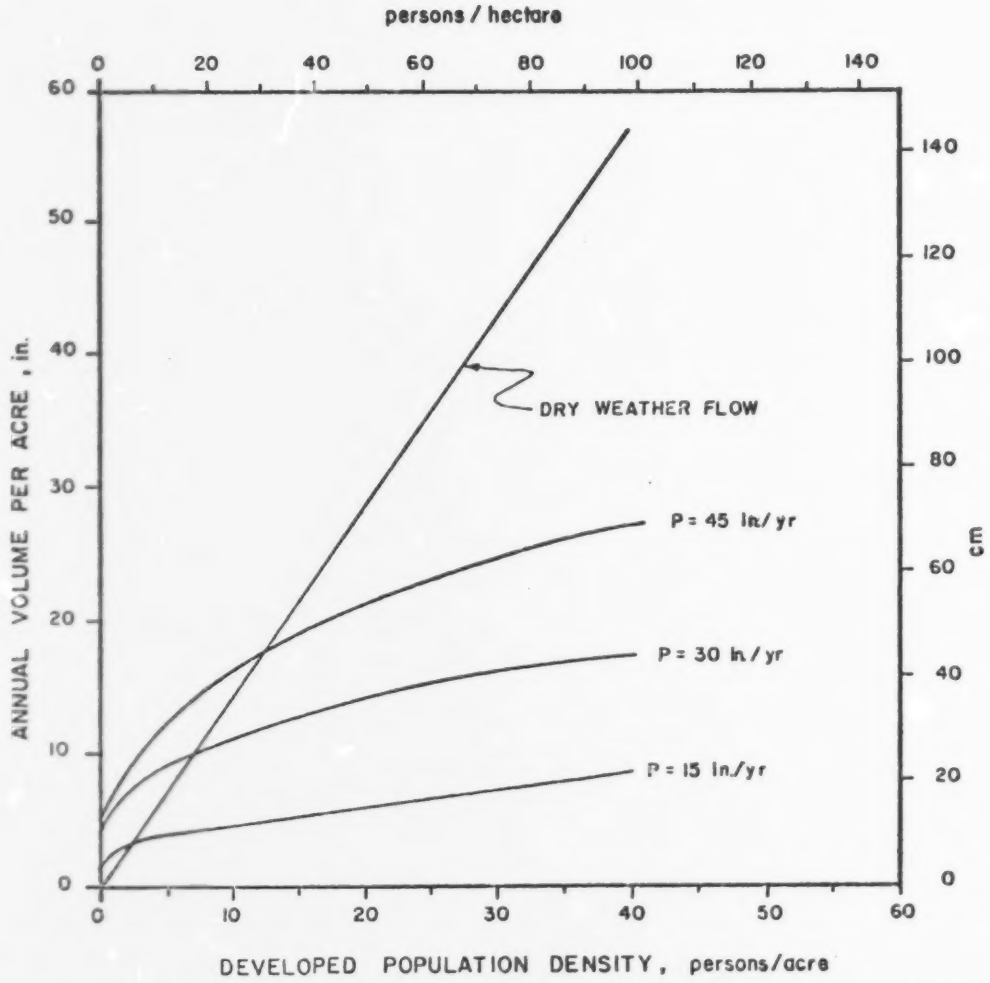


FIGURE 7. COMPARATIVE MAGNITUDE OF ANNUAL WET- AND DRY-WEATHER FLOWS

4.3 Quality Parameters

4.3.1 Parameter definitions

Quality analyses may be performed at several levels of detail, ranging from an explicit formulation of runoff quality for small subcatchments within a city, to a broad representation of pollutant loads for an entire urbanized area or province. It has been necessary to consider the entire spectrum during the course of this study.

It is unfortunate that perhaps the only consistent remark about runoff quality analysis in general is that data and results of previous studies are so remarkably inconsistent. Few studies have been made of

characteristics of street litter, and they offer a wide range of values of concentrations and loads. Effluent data show a similar scatter. However, it is necessary that a decision be made regarding actual values for use in the analysis. This section will describe methods used for predicting runoff quality, data required for their use, and final results used in this study.

Urban runoff quality may be characterized by a variety of parameters. However, the list is generally shortened for modelling purposes to those characteristic of solids, oxygen demand, health hazards and aquatic growth potential, as indicated in Table 20. It is discouraging that even at this juncture, a serious problem of definition of terms arises because of various possibilities for analyzing and reporting quality parameters. The assurance that analyses have been performed according to Standard Methods [27] is not enough information. For example, solids are sometimes reported as "residue" instead of solids, and "filterable residue" instead of "dissolved solids", because of the nature of the evaporation and filtration techniques utilized in the chemical analyses. Generally, "solids" and "residue" are synonymous, and "solids" will be used in this report. Another problem arises from the fact that pollutants may be in both soluble and insoluble forms. Some studies report concentrations of only the soluble portions of, say, BOD and PO_4, leading to unrealistically low values if the reader mistakenly thinks of them as total (soluble plus insoluble) concentrations. On the other hand, it is important to know the relative soluble-insoluble fractions of pollutants since this has a major impact upon treatability. That is, pollutants that appear as suspended solids are relatively easy to remove (e.g., by sedimentation) compared to those that are soluble.

To further complicate the picture, no clear relationship exists between data derived from studies of surface litter (gathered by sweeping, vacuuming, flushing) and those resulting from analysis of the runoff itself (e.g., samples of storm and combined sewerage effluent). Thus, a mixture of data exists, derived from both surface and effluent sources. However, there is no study in which samples of both types have

TABLE 20. TYPICAL QUALITY PARAMETERS OF URBAN RUNOFF MODELS

Quality Characteristic	Representative Quality Parameters
Solids	Surface "Dust and Dirt" Surface "Solids" Total Solids Suspended Solids Dissolved Solids Volatile Solids Settleable Solids
Oxygen Demand	BOD, COD Total Organic Carbon Organic N, NH_3
Health Hazards	Total Coliforms Fecal Coliforms
Aquatic Growth Potential	Ortho-PO_4 Total PO_4 NO_2, NO_3, Total N

been gathered simultaneously. Hence, the relationship between the two is not well defined, and it is difficult to draw conclusions from all data considered together.

In this report, the solids relationship shown in Figure 8 was applied. Note that total solids (TS) is the sum of dissolved solids (DS) plus suspended solids (SS), and that total, dissolved, and suspended solids may be separated into a volatile portion (generally considered the organic portion) and a fixed portion. Volatile solids (VS) will refer to a portion of total solids in this report, unless otherwise indicated. Settleable solids are some fraction of suspended solids. Note, finally, that an upper limit on the size of total solids reported is imposed by the size of the openings in the sampling equipment (e.g., a quarter inch-screen).

Similar diagrams may be prepared for nitrogen and phosphorus, as shown in Figure 9, and Figure 10. For these parameters, it is necessary

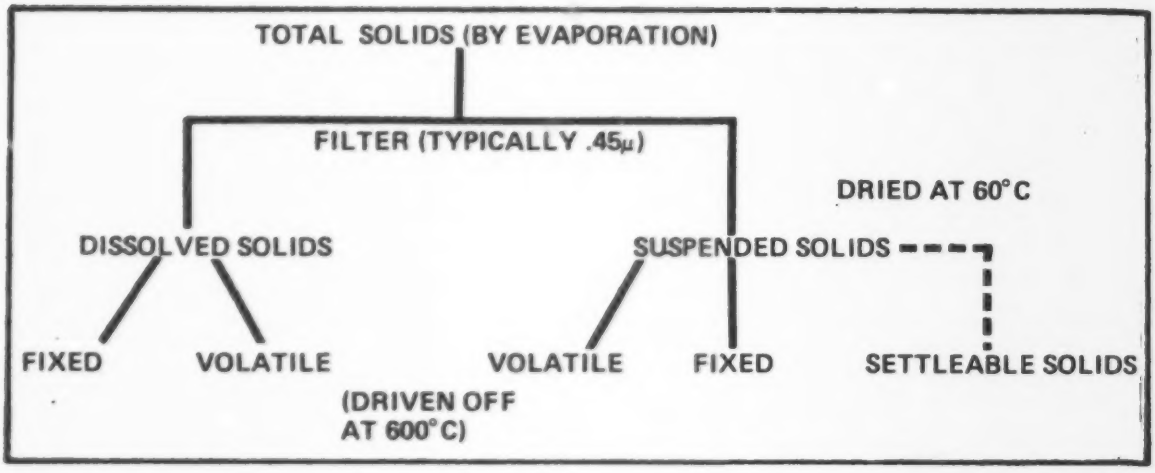


FIGURE 8. RELATIONSHIPS AMONG SOLIDS PARAMETERS

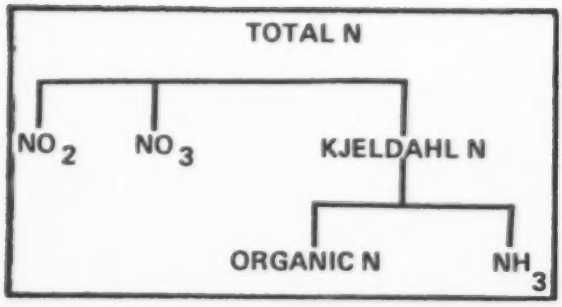


FIGURE 9. RELATIONSHIPS AMONG NITROGEN PARAMETERS

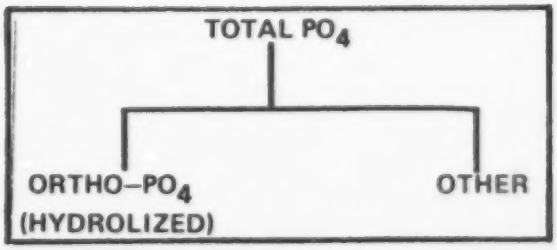


FIGURE 10. RELATIONSHIPS AMONG PHOSPHORUS PARAMETERS

to know whether concentrations are being reported of the element itself (e.g., phosphorus) or the compound (e.g., PO_4), although conversions can readily be made on the basis of the molecular weight of each. Regarding the nitrogen relationships, all concentrations should be reported in terms of N (i.e., NO_2-N, NO_3-N, NH_3-N) in order for mass balances to be performed easily.

4.3.2 Parameters for assessment

For the Ontario assessment, five parameters were used that are representative to some degree of the quality characteristics indicated in Table 20. These are indicated in Table 21.

TABLE 21. QUALITY PARAMETERS USED IN ONTARIO ASSESSMENT

Parameter	Abbreviation
1. Five-Day Biochemical Oxygen Demand	BOD_5 or BOD
2. Suspended Solids	SS
3. Volatile Solids	VS
4. Total Phosphate (as PO_4)	PO_4 or TPO_4
5. Total Nitrogen (as N)	N

Note: All parameters (except suspended solids) are totals that include dissolved and insoluble portions, and are usually determined as in Standard Methods [27]. All are usually reported in concentration units of mg/L (equivalent to ppm).

Five-day BOD was used because of its broad acceptance and traditional role in water quality analysis. Its usefulness is severely impaired by the great difficulty in performing accurate and consistent laboratory analyses. For instance, there is no standard for laboratory comparison, and low-level values (e.g., 10 mg/L) are especially susceptible to errors of up to 100 percent. Moreover, studies have shown that results are affected by the percent dilution and are generally not reproducible [28]. In addition, samples are affected by amounts of heavy metals and other parameters present. Use of COD and/or TOC avoids some of these problems, but their relationship with traditional stream sanitation

analysis (i.e., prediction of dissolved oxygen) is unclear, and most people are used to thinking in terms of BOD. It is used in this study, realizing its limitations.

The other four parameters were used because of general acceptance and availability of data. It should be borne in mind that many options are available for modelling purposes, and the choice of parameters is somewhat arbitrary.

4.4 Quality Prediction Techniques

4.4.1 Pollutant loads

The quality prediction techniques found in most urban runoff models (e.g., SWMM, STORM) rely upon generation of an initial surface load of pollutants. This load is usually expressed in units of lbs, lbs/acre, lbs/curb-mile, lbs/day-acre, or lbs/day-curb-mile (or equivalent metric units). Normalized loads are, of course, multiplied by a unit of area, dry days, etc., to produce an initial mass of pollutants at the start of the storm. Pollutants are then "washed off" during a storm in an exponential fashion in which the amount removed per time step is proportional to the amount present, the runoff rate, and other factors. SWMM [10, 29] and STORM [11, 23] documentation contain details of this methodology. The key factor in prediction of long-term (e.g., annual) pollutant loads from urban areas is, however, the surface loading rates themselves, and most of the following discussion will be devoted to them.

Surface loadings are usually predicted by one of two means: estimates based on surface accumulation data, or estimates based on measurements of effluent concentrations and flows. As mentioned earlier, no one study has performed the analysis both ways, so comparisons are not easily accomplished. However, to obtain the study objective, normalization of loadings rates by some means that could be converted to total mass of pollutants upon multiplication by area, days, and/or other appropriate parameters was necessary. As a result, both methods were utilized in the developments that follow.

4.4.2 Surface accumulation methods

Both SWMM and STORM use this method for prediction of the total soluble mass of pollutants (except for solids) available at the beginning of a storm. For suspended or settleable solids calculations, the total

mass is given since there is no "soluble" portion. The method is based upon the following equation, given in representative English units:

$$P_{i,j} = dd_i \cdot F_{i,j} \cdot G_{L,i} \cdot A_i \cdot N_D + P_o \qquad (23)$$

where: $P_{i,j}$ = total soluble pounds of pollutant p on urban land use i at the beginning of the storm;

dd_i = pounds of accumulated dust and dirt (or "surface solids") per curb mile per dry day;

$F_{i,j}$ = total soluble pounds of pollutant p per pound of dust and dirt found on land use i;

$G_{L,i}$ = number of curb-miles per acre of land use i;

A_i = area of land use i, acres;

N_D = number of dry days since last storm; and

P_o = total soluble pounds of pollutant remaining on land use i at end of last storm.

The dust and dirt accumulation rate is often given in terms of pounds/day per 100 feet of curb instead of curb-miles, but the latter units are used here for ease in comparison with other portions of the report.

The parameter N_D is the number of dry days since the last storm, not the number of days since the last storm or street cleaning operation. This is because, in most cases the interval between storms is less than the street cleaning interval. The latter is generally in the order of several 10's of days and the efficiency of street cleaning operations is uncertain in any event.

The parameters dd_L, $F_{p,L}$, and G_L are functions of land use, L. The dust and dirt loadings, dd_L, and pollutant fractions, $F_{p,L}$, data are shown in Table 22 [31]. These parameters may be updated to some degree, as will be shown. As indicated in Table 22, SWMM assumes that all dust and dirt will pass through a quarter-inch (6 mm) screen and is insoluble, thereby appearing as suspended solids (i.e., the SS fraction, $F_{i,j}$, is 1.0). STORM assumes that only from seven to 17 percent of dust and dirt meets these requirements. Both models assume that settleable solids are about ten percent of suspended. The SWMM assumptions imply that the total of all pollutants is slightly greater than 100 percent of dust and

TABLE 22. PARAMETERS FOR SURFACE POLLUTANT ACCUMULATION USED IN SWMM AND/OR STORM

Parameter	Units	Land Use: Single-family Residential	Multi-family Residential	Commercial	Industrial	Open[a]
Dust and dirt loading, dd_i	lb/day-curb-mile	40.0	121.0	174.0	243.0	79.2
	kg/day-curb-km	11.4	34.4	49.4	69.0	22.5
Pollutant fractions[b], $F_{i,j}$						
SS[a] (SWMM)		1.0	1.0	1.0	1.0	1.0
SS[a] (STORM)		0.111	0.08	0.17	0.067	0.111
Settleable Solids[c] (SWMM)		0.1	0.1	0.1	0.1	0.1
Settleable Solids[c] (STORM)		0.011	0.008	0.017	0.007	0.011
BOD_5		0.005	0.0036	0.0077	0.003	0.005
COD		0.04	0.04	0.039	0.04	0.02
Total PO_4		0.00005	0.00005	0.00007	0.00003	0.00001
Total N		0.00048	0.00061	0.00041	0.00043	0.00005
Grease[a]		0.001	0.001	0.001	0.001	0.001
Total Coliforms	MPN/g	1.3×10^6	2.7×10^6	1.7×10^6	1.0×10^6	0.00

Except as noted, values are for soluble portion and derived from the 1969 APWA Chicago study [31].

[a]All values assumed.
[b]Fraction refers only to soluble fraction of dust and dirt (except solids).
[c]All values assumed at 10% of value for SS.

dirt, while the STORM assumptions imply that the total of all pollutants is only about 12 percent of dust and dirt.

The insoluble portion of pollutants is accounted for (in SWMM and STORM) by addition of a fraction of the solids concentration to predicted effluent concentrations (of the soluble portion). For example, SWMM adds five percent of the SS concentration to the soluble BOD concentration to obtain total BOD, on the basis of calibration of the original SWMM in San Francisco. This is because of the reliance upon the 1969 APWA Chicago data in which only soluble fractions were reported. It is obvious that equation (23) could be used to predict the total (soluble plus insoluble) mass of surface pollutant accumulation simply by a redefinition of terms (and use of appropriate revised numbers). This would facilitate quality calibration of the models and probably be as accurate, considering the available data. Final surface pollutant loads derived subsequently will refer to total pounds of pollutants.

Starting with the Chicago study and followed subsequently by others, it has become customary to report data in terms of mass of pollutants per unit length of curb, on the assumption that the curbs and gutters represent the main source area for acquisition of pollutants by the storm runoff. In order to obtain loadings on a unit area basis, it is necessary to obtain the length of curb per area for each land use, thus defining the parameter $G_{L,i}$ in equation (23).

It is expected that $G_{L,i}$ would be a function of land use, which in turn is a function of population density, PD. Curb length (taken as twice street length) was related to population density in the Washington, D.C., area by Graham et al [25]. Their data, augmented by data from other parts of the United States by APWA [3], resulting in:

$$G_L = 0.0782 - 0.0668 \cdot 0.839^{PD_d} \qquad (24)$$

where: G_L = curb length per area, mile/acre, and
PD_d = developed population density, persons/acre.

Equation (24) seems to work well for residential areas, but the curb length concept is troublesome when one is evaluating commercial, industrial, or open areas. For example, what is the equivalent curb length of a shopping center? Data from other sources are compared in Table 23.

An average of the Tulsa [32] and Ontario data was used in the analysis. Ontario data were not used by themselves because of possible differences in measurement techniques which may affect relationships with pollutant loadings that follow. In addition, it will be seen that ratios of curb lengths between different land uses are the important functions; these change little between cities. Specific data for residential areas were used in lieu of equation (24), since the equation was developed to predict curb length as a function of population density average over all land uses. However, the equation may be used when considering an overall urban area.

To summarize, the surface accumulation methods are convenient for modelling purposes and illustrate the linkages between various causative factors. The key missing factor is a link between the surface loads and effluent loads that has been verified by measurements of both. Until this is accomplished, such a link must be hypothesized in its

TABLE 23. MEASURED CURB LENGTHS FOR VARIOUS LAND USES

	Tulsa[33]			10 Ontario Cities[a]			Average of Two Locations for Use in Study		
	mile/ acre	km/ha	100 ft/ acre	mile/ acre	km/ha	100 ft/ acre	mile/ acre	km/ha	100 ft/ acre
Residential	0.076	0.30	4.01	0.067	0.27	3.56	0.072	0.29	3.78
Commercial	0.081	0.32	4.28	0.057	0.23	2.99	0.069	0.28	3.64
Industrial	0.042	0.17	2.22	0.026	0.10	1.35	0.034	0.14	1.78
Park	0.042	0.17	2.22	–	–	–	–	–	–
Open	0.016	0.063	0.84	0.015	0.059	0.81	0.024[b]	0.097[b]	1.29[b]
Institutional	–	–	–	0.030	0.12	1.66	–	–	–

[a] *Average of data collected by University of Florida, 1975, Guelph, Kingston, Kitchener-Waterloo, Milton, St. Catharines, Sault Ste. Marie, Thunder Bay, Toronto, Windsor.*

[b] *Average of open plus park*

mathematical formulation, as done in SWMM and STORM. However, equation (23) is used in developments that follow to relate loadings between different land uses and pollutants, hence the reason for the previous developments. The other side of the coin, that is, results derivable from effluent data alone, will be discussed next.

4.4.3 Effluent concentration methods

Many studies in recent years have reported measured concentrations of pollutants in storm and combined sewer discharges. If the flow rate is also known, the mass flow pollutograph may be determined (e.g., lbs/min of BOD) and integrated to produce the total mass emission for the storm discharge. When distributed over the area of the catchment and divided by the number of dry days preceding, normalized loadings (e.g., mass-BOD/area-day) may be determined. Some studies report these values directly, while others report a lesser amount of information. In general, the surface loading may be deduced from a measured flow-weighted average concentration and assumed runoff quantity:

$$M = P \cdot C \cdot CR \cdot \rho \qquad (25)$$

where: M = surface loading, mass/area-time;

P = precipitation, depth/time;

C = average concentration = mass pollutant per mass of of total sample;

CR = runoff coefficient; and

ρ = water density, mass/volume

For an individual storm, preceded by N_D dry days, the total depth of precipitation, P_S, may be given. Then,

$$M = \frac{P_S \cdot C \cdot CR \cdot \rho}{N_D} \tag{26}$$

For annual average computations it may be assumed that, on an average basis,

$$P_S = P/n \tag{27}$$

and

$$N_D = 365/n \tag{28}$$

where: P = average annual precipitation, depth/year;

N_D = average number of days between storms; and

n = average number of storms per year.

Equation (25) may thus be used to compute average annual values since it results from substitution of equations (27) and (28) into equation (26).

Equation (25) may be converted to convenient units. For instance,

$$M\left(\frac{lb}{day\text{-}acre}\right) = P\left(\frac{in}{yr}\right) \cdot C\left(\frac{lb}{10^6\ lb}\right) \cdot CR \cdot 62.4\left(\frac{lb}{ft^3}\right)$$

$$\cdot \frac{43.560}{acre}\ ft^2 \cdot \frac{ft}{12\ in.} \cdot \frac{yr}{365\ day}$$

or

$$M = 6.206 \times 10^{-4} \cdot P \cdot C \cdot CR \tag{29}$$

where: M = average surface loading, lb/day-acre;

P = annual precipitation, in/yr;

C = pollutant concentration, mg/L or ppm; and

CR = runoff coefficient, fraction.

Use of equation (29) presents several difficulties. It is inherently an average, and is susceptible to the assumptions of equations (27) and (28). It requires the use of a flow-weighted average concentration. Unfortunately, such values are seldom reported in the literature,

if indeed any specification is made as to the types of "average" concentration presented. Runoff is generated by the simplest of methods, that of a runoff coefficient, with all of its well-documented errors.

On the other hand, measured concentrations do in fact represent the real amount of pollutants being discharged, and thus incorporate all of the unknown factors involved in trying to generate surface loads coupled with a wash-off and transport mechanism. These include such factors as dust fall, air pollution, and several others not specifically addressed in this study. Furthermore, for purposes of the assessment performed in this study, very simple methods of runoff and quality generation must be employed. Hence, equation (29) is consistent with other levels of analysis used in this research.

In the same manner that surface accumulations could be considered functions of population density and land use, so can surface loadings derived from effluent data. In particular, both the concentration and runoff coefficient are clearly such functions; the latter has been discussed previously. In order to ascertain the functional relationship between the surface loadings and population density, available data for residential areas for which population density is given have been tabulated. Derived surface loadings are given in Table 24. The cities included in the table all had data for residential areas for which population density was specified and from which surface loadings could be derived. The list is not meant to be exclusive, but represents data that were readily available during the study.

The vast disparity among all the data may be seen in Figure 11. Both separate and combined loadings vary by more than an order of magnitude. Unfortunately, the variation persists if normalized by dividing by annual precipitation (not shown). Three cities produced very high results compared to the bulk of the data: Atlanta, Bucyrus, and Durham. The reason for this is primarily variation from strictly residential land use. In addition, the open channels sampled in Durham had characteristics of open sewers. The values were so high as to be inconsistent with the rest of the data and were omitted from subsequent analysis. The remaining data still showed considerable scatter, but were utilized to aid in deriving required relationships.

TABLE 24. SURFACE BOD LOADINGS FOR RESIDENTIAL AREAS AS DERIVED FROM EFFLUENT MEASUREMENTS

City	Site or Station[a]	Sewer System	Catchment Area ac	(ha)	Annual Precip. in.	(cm)	Runoff Coef.	BOD Conc. mg/L	Surface Loading lb/ac-day	(kg/ha-day)	Population Density Persons/ac	(persons/ha)	Source
Tulsa	3	Separate	550	(223)	48	(122)			0.0381	(0.0428)	7.13	(17.61)	32
	5	Separate	507	(205)					0.0901	(0.1012)	8.93	(22.06)	
	7	Separate	197	(80)					0.0417	(0.0468)	11.55	(28.53)	
	8	Separate	211	(85)					0.0899	(0.1009)	11.37	(28.08)	
	9	Separate	64	(26)					0.0544	(0.0611)	13.67	(33.76)	
	11	Separate	815	(330)					0.0963	(0.1081)	9.57	(23.64)	
	13	Separate	212	(86)					0.0679	(0.0762)	2.36	(5.83)	
	15	Separate	74	(30)					0.0688	(0.0772)	11.22	(27.71)	
Bucyrus	8	Combined	179	(72)	35	(89)	0.39	120	1.017	(1.142)	11.7	(28.9)	33
	17	Combined	614	(249)			0.41	107	0.953	(1.070)	9.1	(22.5)	
	23	Combined	378	(153)			0.35	108	0.821	(0.922)	5.0	(12.4)	
Atlanta	Confed. Ave.	Combined	1,129	(457)	48	(122)	0.31	210	1.94	(2.178)	10.9	(26.9)	34
	Blvd.	Combined	2,421	(980)			0.42	84	1 05	(1.179)	16.6	(41.0)	
	McDan St.	Combined	968	(392)			0.42	286	3.58	(4.019)	13.2	(32.6)	
	Harlan	Separate	954	(386)			0.33	7	0.069	(0.077)	9.7	(24.0)	
	Casplan	Separate	517	(209)			0.56	20	0.334	(0.375)	7.3	(18.0)	
	Fed. Pris.	Separate	1,498	(606)			0.31	26	0.240	(0.269)	4.8	(11.9)	
Roanoke	Trout Run	Separate	997	(404)	34	(86)			0.0363	(0.0408)	11.0	(27.2)	35
	Murray Run	Separate	909	(368)					0.0428	(0.0481)	6.6	(16.3)	
	24 St.	Separate	1,034	(419)					0.0233	(0.0262)	9.7	(24.0)	
Milwaukee	Hawley Rd.	Combined	495	(200)	31	(79)	0.40	49	0.377	(0.423)	35.0	(86.5)	36

Note: Surface loadings are taken directly from the source if given, or derived from mass emission data. Otherwise, equation 29 is used (for cities for which runoff coefficient and BOD concentration are listed).

TABLE 24. (CONT'D)

City	Site or Station[a]	Sewer System	Catchment Area ac	(ha)	Annual Precip. in.	(cm)	Runoff Coef.	BOD Conc. mg/L	Surface Loading lb/ac-day	(kg/ha-day)	Population Density Persons/ac	(persons/ha)	Source
Wash., D.C.	Good Hope Run	Separate	265	(107)	41	(104)			0.063	(0.071)	37.6	(92.9)	37
	B4	Combined	105	(43)					0.247	(0.277)	43.6	(107.7)	
	G4	Combined	222	(90)					0.381	(0.428)	52.6	(129.9)	
Des Moines	S-1	Separate	315	(128)	31	(79)	0.10	48	0.093	(0.104)	7.4	(18.3)	38
	S-3	Separate	356	(144)			0.10	63	0.121	(0.136)	5.3	(13.1)	
	0-3	Combined	4,050	(1,640)			0.15	69	0.199	(0.223)	7.5	(18.5)	
	0-6	Combined	5,600	(2,267)			0.15	95	0.275	(0.309	8.3	(20.5)	
	0-8	Combined	1,350	(547)			0.15	68	0.197	(0.221)	10.9	(26.9)	
	0-8A	Combined	927	(375)			0.15	77	0.222	(0.249)	10.9	(26.9)	
Cincinnati	Mt. Washington	Separate	27	(11)	40	(102)			0.0904	(0.1015)	9.0	(22.2)	39
Durham	E-1	Separate	56	(23)	45	(114)	0.29[b]	25	0.202	(0.227)	14.9	(36.8)	40
	W-1	Separate	169	(68)			0.35[b]	61	0.596	(0.669)	2.6	(6.4)	
	W-2A	Separate	69	(28)			0.34[b]	38	0.361	(0.405)	11.0	(27.2)	
	W-2B	Separate	138	(56)			0.36[b]	51	0.513	(0.576)	13.4	(33.1)	
	N-1	Separate	183	(74)			0.36[b]	71	0.714	(0.802)	4.2	(10.4)	
Seattle	Low Dens.	Separate	c		36	(91)			0.04	(0.045)	11.0[d]	(27.2)	41
	Med. Dens.	Separate	c						0.07	(0.079)	22.0[d]	(54.3)	
	High Dens.	Separate	c						0.13	(0.146)	30.0[d]	(74.1)	
Windsor	Labadie Rd.	Separate	30	(12)	33	(84)			0.059	(0.066)	20.0	(49.4)	42

[a] *Site or station as listed in source documentation.*

[b] *Value computed using imperviousness.*

[c] *Hypothetical area based on measured data.*

[d] *Assumed on basis of dwelling units per acre.*

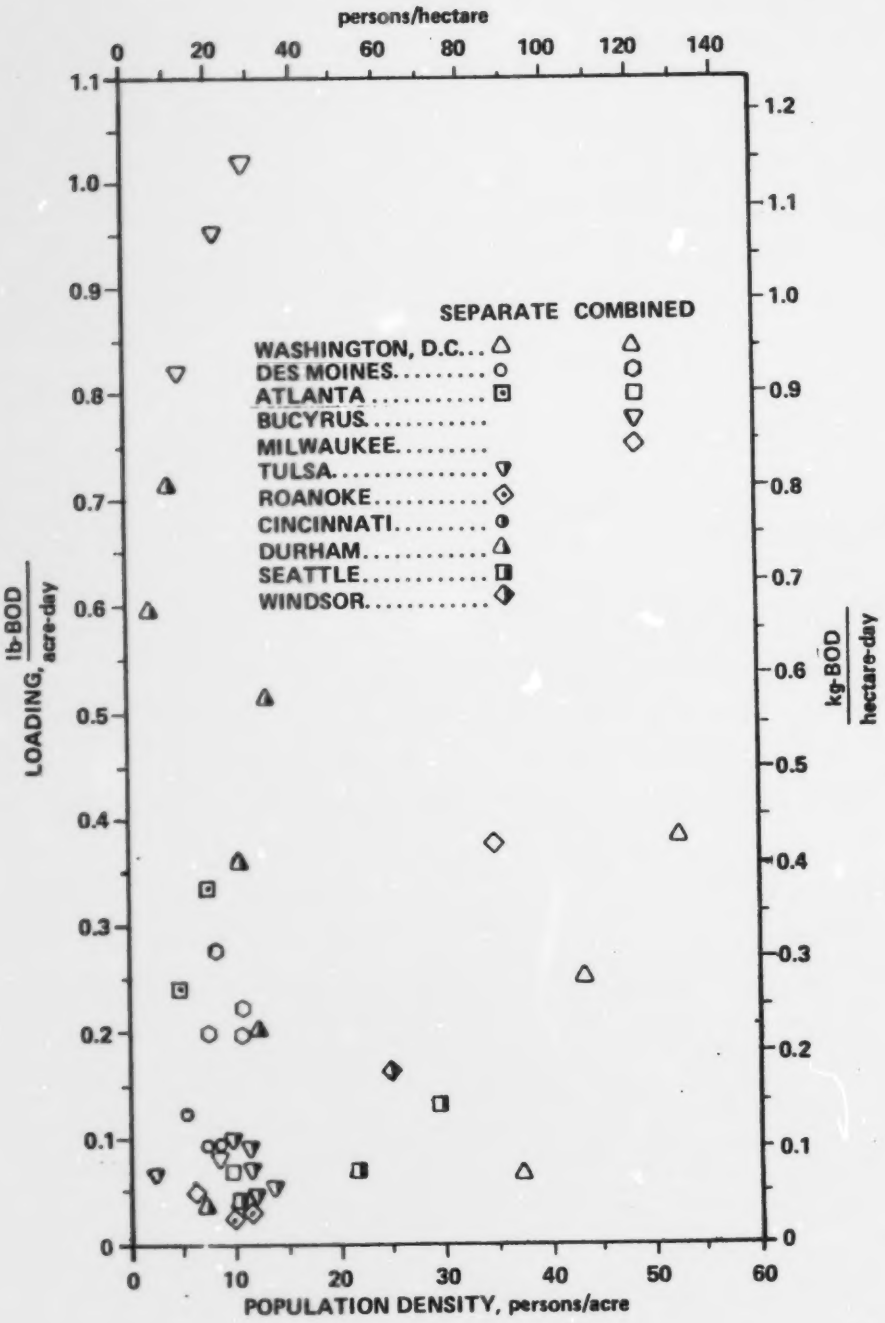


FIGURE 11. RESIDENTIAL BOD LOADINGS vs POPULATION DENSITY

The data of Droste [42] from Windsor were about the only data for the study region that provided both a BOD loading estimate and population density for a residential area. An earlier study in Windsor [43] also provided these required data but was conducted on a developing area that included construction activities and was considered somewhat atypical by Droste [42]. Hence, it was not included in Table 24.

Other studies of importance to the analysis included work in Halifax that had been published [44, 45] as well as work in Toronto, Burlington, and Aurora, sponsored by Environment Canada that had not yet been completed. Of these, only the latter Halifax study of Bhatia [45] provided BOD loads of the type required in this analysis, but data were taken there for only three months in 1971, and it was somewhat questionable as to whether they were representative of a whole year. (Almost all the data included in Table 24 were taken over a period of several months.) In addition, population densities were not given. However, the average surface runoff BOD load calculated for the 2.18 acre (0.9 ha) Cambridge St. residential area of 0.038 lb-BOD/acre-day (0.042 kg-BOD/ha-day) is within the range presented in Table 24 and Figure 11. Clearly a synthesis of data from current studies in Ontario and elsewhere across Canada will provide better estimates of parameters needed for this type of analysis.

4.5 Pollutant Load Prediction for Ontario Assessment

4.5.1 Form of equation

Surface pollutant loads generated by the pollutant load estimating equation are assumed to "wash off" on an annual basis for purposes of the assessment. Hence, they must be representative of actual measured effluent loads. Moreover, they should be functionally related to causative factors in a reasonable manner. They are expected to be functions of land use and population density. In addition, there are apparent observed geographical variations in, say, dust and dirt loadings, although it is not immediately obvious as to why these loadings should differ in a commerical or industrial area from one point in the country to another, other than on the basis of climate.

The key climatic parameter is precipitation, since the more precipitation that occurs, the more likely it is that pollutants will be washed off the surface and appear as effluent loads instead of being removed by other means such as street sweeping or wind. Total annual pollutant loads from storm runoff are lower in arid regions for this reason [47]. Precipitation includes both rain and snow, on an annual basis, incorporating the assumption that pollutants accumulate during periods of snow cover and eventually are washed off during periods of melt.

These considerations led to the selection of a prediction equation, in which the loading is proportional to precipitation, for all land uses. It is also proportional to a function of population density for residential areas which is intended to account for many other implicit factors such as age of area, imperviousness, runoff coefficient, etc., all of which are functions of population density. This formulation was easily applied because precipitation and population density data were readily available. However, these parameters were about the only ones (other than areas) that were available, ruling out more complicated functions. The loading, M, is thus represented functionally as:

$$M = \alpha \cdot f_1(P)\, f_2(PD) \tag{30}$$

where the coefficient α and functions f_1 and f_2 are determined below. The procedure followed develops appropriate parameters for residential areas first, which are then extended to other land uses.

4.5.2 Precipitation function

If average BOD loadings for the cities in Table 24 (omitting Atlanta, Bucyrus, and Durham) are plotted versus annual precipitation (not shown), no clear relationship is indicated. Hence, the data are simply averaged to obtain the factor α and $f_1(P)$ of equation (30) for BOD. That is, it is assumed that the loadings are directly proportional to precipitation, such that zero precipitation generates zero storm water pollution. This is supported by equation (29). Hence,

$$f_1(P) = P \tag{31}$$

and the parameter α is obtained as an average of the seven remaining cities in Table 24 for which separate data are available. Thus, for BOD for residential areas,

$$\alpha = \frac{1}{7} \sum_{i=1}^{7} \frac{\text{loading}_i}{P_i} = 0.00219 \frac{\text{lb-BOD}}{\text{ac-day-in.}}$$

$$= 0.799 \frac{\text{lb-BOD}}{\text{ac-yr-in}} = 0.353 \frac{\text{kg-BOD}}{\text{ha-yr-cm}} \quad (32)$$

Annual average BOD loadings for residential areas are now predicted by

$$M = 0.799 \cdot P \cdot f_2(PD_d) \quad (33)$$

where: M = annual average BOD loading for separate sewered, residential areas, lb-BOD/ac-yr;

P = annual precipitation, inches; and

PD_d = developed population density, persons/acre.

For combined areas the equation is identical, except that a parameter β is employed instead of α to distinquish between combined and separate areas. For BOD for residential areas, the value of β is computed using average values for Des Moines, Milwaukee, and Washington, D.C. from Table 24.

$$\beta = \frac{1}{3} \sum_{i=1}^{3} \frac{\text{loading}_i}{P_i} = 0.00902 \frac{\text{lb-BOD}}{\text{ac-day-in}}$$

$$= 3.29 \frac{\text{lb-BOD}}{\text{ac-yr-in}} = 1.46 \frac{\text{kg-BOD}}{\text{ha-yr-cm}} \quad (34)$$

Annual BOD loadings for residential areas served by combined sewers are thus,

$$M = 3.29 \cdot P \cdot f_2(PD_d) \quad (35)$$

where parameters are as previously defined.

It may be seen that, for the same population density and precipitation, combined BOD loadings are 3.29/0.799 = 4.12 times higher than separate loadings. This agrees with an independent survey of available data by Lager and Smith [46] in which average BOD concentrations in combined sewage of 115 mg/L are 3.83 times greater than the average BOD concentration of 30 mg/L in separate sewers. The difference in loadings is due mainly to residual matter left in conduits between storms, since simple mixing of storm water and dry-weather flow, or differences in population density between separate and combined sewer areas, will not explain the four-fold variation in concentrations and loadings.

4.5.3 Population function

The data in Table 24 and Figure 11 incorporate all the available information about the relationship of BOD loadings with population density implied by equations (29) and (30). In order to extend the data base slightly further, it is assumed that combined area loadings increase with population density, PD, in the same manner as do separate area loadings. The data base can then be extended slightly by normalizing by the average loading for separate and combined areas. Omitting the data from Atlanta, Bucyrus, and Durham, Table 25, was prepared. Finally, the data of Table 25 was plotted, as shown in Figure 12. A point has been added that represents the loading in open space of 0.00982 lb-BOD/ac-day (0.0110 kg-BOD/ha-day) where presumably the population density is zero. (The derivation of this value is shown later.)

Inspection of Figure 12 shows such scatter that no statistically significant relationship is likely to be derived from the data. Rather, an argument must be made upon the expected form of the functional relationship, and the data used only to obtain a calibration. This relationship is expected to be similar to those developed earlier for imperviousness and curb length, namely increasing rapidly at low population densities and leveling off at high ones.

The concentration of storm water pollutants is M/AR, or

$$M/AR = \frac{\alpha \, P \, f_2(PD_d)}{K[0.15+0.751]P} \qquad (36)$$

where: $I = 0.096 \, PD_d^{+0.573} - 0.391 \log_{10} PD_d$, or

$$I \simeq 0.096 \, PD_d^{0.54} \qquad (37)$$

and K is a conversion factor, for example, the value that appears in equation (29). Depression storage is omitted in the approximation of annual runoff. Thus,

$$M/AR \simeq \frac{\alpha \, [f_2 PD_d]}{K[0.15+0.072 \, PD_d 0.54]} \qquad (38)$$

TABLE 25. NORMALIZED BOD LOADING DATA

	Average Loading lb-BOD/ ac-day (kg-BOD/ ha-day)	City	Loading/ Ave. Loading	Population Density Persons/ac	Persons/ha
Separate Areas	0.0693 (0.0778)	Tulsa	0.550	7.13	17.61
			1.300	8.93	22.06
			0.0602	11.55	28.53
			1.297	11.37	28.08
			0.785	13.67	33.76
			1.390	9.57	23.64
			0.980	2.36	5.83
			0.993	11.22	27.71
		Roanoke	0.524	11.0	27.2
			0.617	6.6	16.3
			0.336	9.7	24.0
		Wash., D.C.	0.909	37.6	92.9
		Des Moines	1.342	7.4	18.3
			1.746	5.3	13.1
		Cincinnati	1.305	9.0	22.2
		Seattle	0.577	11.0	27.2
			1.010	22.0	54.3
			1.876	30.0	74.1
		Windsor	0.851	20.0	49.4
Combined Areas	0.271 (0.304)	Wash., D.C.	0.911	43.6	107.7
			1.405	52.6	129.9
		Milwaukee	1.391	35.0	86.5
		Des Moines	0.734	7.5	18.5
			1.014	8.3	20.5
			0.727	10.9	26.9
			0.819	10.9	26.9

Note: Values obtained from Table 24, omitting data from Atlanta, Bucyrus and Durham.

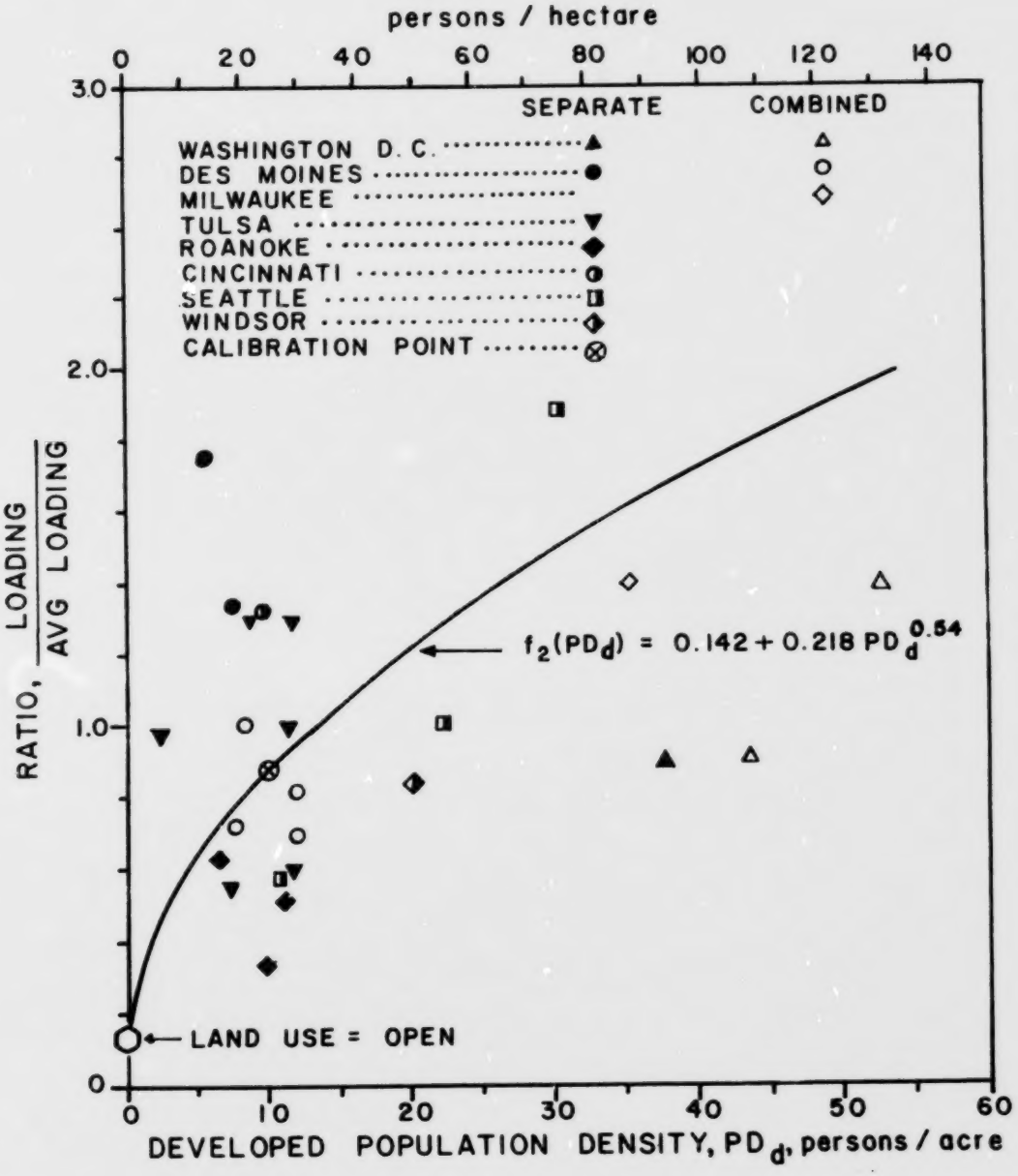


FIGURE 12. NORMALIZED BOD LOADINGS VS POPULATION DENSITY

Data are from Table 25

It is assumed that $f_2(PD_d)$ is

$$f_2(PD_d) = a + b\ PD_d^{m} \tag{39}$$

where: $a = 0.142$ = value at $PD_d = 0$,

and developed population density will be used for consistency. Note that, depending on the assumed value of m, the concentration of storm water pollution will vary accordingly. Since no firm arguments can be made on the nature of the concentration function, it will be assumed that m is equal to the approximate exponent in the runoff equation or m = 0.54. Thus, $f_2(PD_d) = 0.142 + b\ PD_d^{0.54}$. Lastly, all data points with a PD_d ranging from 5 to 15 persons per acre (12 to 37 persons per ha) are averaged to obtain a calibrated value of $f_2(PD_d) = 0.895$ at 10 persons per acre (25 persons per ha). This range is chosen because data from most cities fall within it. Thus, the final equation is

$$f_2(PD_d) = 0.142 + 0.218\ PD_d^{0.54} \tag{40}$$

where: PD_d = developed population density, persons per acre.

The reasonableness of equation (40) can be checked by estimating the variation in concentration as a function of population density. From equations (33) and (40), the annual BOD loading is:

$$M = 0.799 \cdot P \cdot (0.142 + 0.218\ PD_d^{0.54}) \tag{41}$$

and annual runoff, AR, using the approximate New Jersey [26] equation for imperviousness is:

$$AR = [0.15 + 0.75\ (0.096)\ PD_d^{0.54}] \cdot P \tag{42}$$

Thus,

$$M/AR = \frac{0.113 + 0.174\ PD_d^{0.54}}{K[0.15 + 0.072\ PD_d^{0.54}]} \tag{43}$$

Using K = 0.227 for these units, this ratio, which is plotted on Figure 13, shows concentration increasing with population density, which does seem to be reasonable. The range of average annual concentrations is lower than values shown in Table 24 since it represents the average over the total residential area of a city. Unquestionably, the data base for estimating pollutant loads is very weak, and the resulting estimating equation, supported by such a weak foundation, should be used with extreme caution.

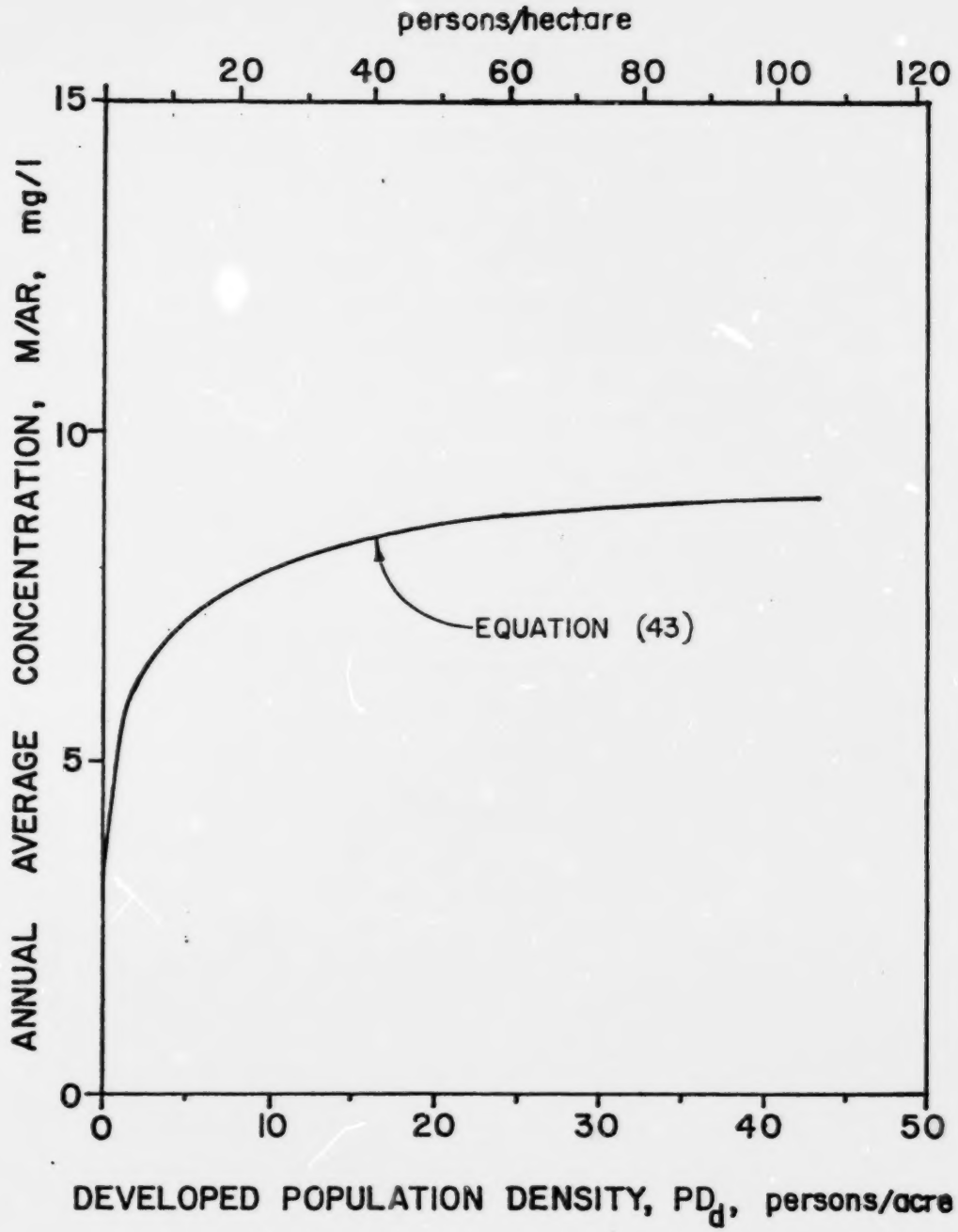


FIGURE 13. ANNUAL AVERAGE RESIDENTIAL BOD CONCENTRATION USING ESTIMATING EQUATION

4.5.4 Conversion for alternate land uses and pollutants

Different pollutants and land uses will generate different loadings for at least three reasons. First, the dust and dirt loadings for different land uses differ. Second, the conversion factor of curb length per area is different for different land uses. Third, the pollutant fractions (as a fraction of dust and dirt) are different for different land uses. These factors are used to extend the equation developed for BOD for residential areas to similar equations for commercial, industrial and open land uses and for suspended solids, volatile solids, total PO_4, and total N.

It is assumed that fractions and ratios of pollutants as they appear in effluent will be the same as those determined from analysis of surface accumulation data. The parameters shown in Table 26 are used for conversion purposes. They are selected from the extensive survey material prepared by APWA [3]. Where no data are available for pollutants as a fraction of surface dust and dirt, use is made (as a second choice) of similar data developed for pollutants as a fraction of total solids (TS).

The BOD data are first converted to other land uses, using equation (23) as indicated below:

$$\alpha\,(i,\ BOD) = \alpha\,(res,\ BOD) \cdot \frac{dd_1}{dd_{res}} \cdot \frac{G_{L,i}}{G_{L,res}} \cdot \frac{F_{i,BOD}}{F_{res,BOD}} \qquad (44)$$

where: dd_i = dust and dirt accumulation on land use i, lb/day-curb mile;

$G_{L,i}$ = curb miles per acre of land use i from Table 23, and

$F_{i,BOD}$ = fraction of dust and dirt that is BOD on land use i.

For example, the parameter α for BOD for commercial land use for separate areas is:

$$\alpha\,(com,\ BOD) = 0.799\ \frac{166 \times 7190}{353{,}465} \cdot \frac{0.069}{0.072}$$

$$= 2.59\ \frac{lb\text{-}BOD}{ac\text{-}yr\text{-}in} = 1.14\ \frac{kg\text{-}BOD}{ha\text{-}yr\text{-}cm} \qquad (45)$$

where the number of 353,465 is the average product of dd • F for BOD is equal to:

TABLE 26. SURFACE LOADING AND POLLUTANT FRACTION DATA

	Residential						
	Single Family	Multi Family	Average	Commercial	Industrial	Open[a]	All Date
Dust and Dirt (DD) Accumulation $\frac{lb}{day\text{-}curb\ mile}$	62	113	87.5	166	319	50	159
$\frac{kg}{day\text{-}curb\ meter}$	17	32	24.8	47	90	14.2	45
BOD – ppm of DD	5,260	3,370		7,190	2,920		
ppm of total solids (TS)[a]			29,840	83,800	25,850	18,990	
Total PO_4 – ppm of DD							170
ppm of TS[a]						1,670	
Total N – ppm of DD							664[b]
ppm of TS[a]						10,170[c]	
Suspended Solids – ppm of TS[a]			609,200	582,300	619,500	453,200	
Volatile Solids – ppm of TS[a]			353,000	367,700	306,100	437,500	

Except as noted, all data are from Table 82 [3]. Missing entries are not given in original table or not used in analysis.

[a]Values taken from Table 19 [3].
[b]Sum of K-N plus NO_3-N.
[c]Value for organic N only.

$$\frac{62 \times 5{,}260 + 113 \times 3{,}370}{2}$$

After determination of BOD for each land use, i, other quality parameters, j, are computed on the basis of relative values of the fractions, F. Thus,

$$\alpha\,(i,j) = \alpha(i,BOD)\,\frac{F_{i,j}}{F_{i,BOD}} \qquad (46)$$

For example, the parameter α for total PO_4 (TPO_4) in commercial areas is:

$$\alpha\,(com,\ TPO_4) = 2.59 \times \frac{170}{7{,}190} = 0.0612\ \frac{lb\text{-}TPO_4}{ac\text{-}yr\text{-}in} \qquad (47)$$

$$= 0.027C\ \frac{kg\text{-}TPO_4}{ha\text{-}yr\text{-}cm}$$

For total nitrogen, N, in residential areas the calculation is similar but includes the average product of dd • F,

$$\alpha\,(res,N) = \frac{0.799 \cdot 664 \cdot (62 + 113)/2}{353{,}465} = 0.131\ \frac{lb\text{-}N}{ac\text{-}yr\text{-}in} \qquad (48)$$

$$= 0.058\ \frac{kg\text{-}N}{ha\text{-}yr\text{-}cm}$$

For open land use, and for suspended solids and volatile solids, no data are available for fractions of dust and dirt, so fractions of total solids are used for values of F in the ratios. For example, for suspended solids in commercial areas,

$$\alpha\,(com,SS) = 2.59 \times \frac{582,300}{83,800} = 18.0\ \frac{lb\text{-}SS}{ac\text{-}yr\text{-}in} \qquad (49)$$

$$= 7.95\ \frac{kg\text{-}SS}{ha\text{-}yr\text{-}cm}$$

Computations for combined areas are carried out in the same manner to calculate the β parameters.

Results from the U.S. assessment show that there is a point after which the magnitude of street sweeping frequency has no effect on the computed values of average annual pollutant concentrations [2]. In Des Moines, Iowa, if the streets are swept less frequently than every 20 days, then the STORM model, which accounts for street sweeping, does not show any significant reduction of pollutant load. For intervals up to 20 days, a linear buildup may be assumed. Thus, the final estimating equation includes a street sweeping factor γ as a function of the sweeping interval, N_s, in days, i.e.

f/20 if interval of street sweeping, f, is such that

$$\gamma = \begin{cases} N_s/20 \text{ if } 0 \leq N_s \leq 20 \text{ days} \\ 1.0 \text{ if } N_s > 20 \text{ days} \end{cases} \qquad (50)$$

No variation due to type of sewer system is included. For this assessment the street sweeping intervals exceeded 20 days so it was unnecessary to take explicit account of this factor. The final result is shown in Table 27.

Use of the same adjustment factors for combined and separate areas leads to the same ratio $\beta/\alpha = 4.12$ for all entries in the table. On the basis of measured concentration data [46], the assumption appears valid except for solids, wherein some studies have shown higher ratios of volatile solids to suspended solids, for example, in combined sewage than in storm runoff alone [44].

The BOD loadings are compared to dry-weather flow loadings in Table 28 for residential land use. Storm and combined runoff can be seen to be

TABLE 27. POLLUTANT LOADING FACTORS FOR ONTARIO ASSESSMENT

The following equations may be used to predict annual average loading rates as a function of land use, precipitation and population density.

Separate Areas: $M_s = \alpha(i,j) \cdot P \cdot f_2(PD_d) \cdot \gamma \frac{lb}{acre\text{-}yr}$

Combined Areas: $M_c = \beta(i,j) \cdot P \cdot f_2(PD_d) \cdot \gamma \frac{lb}{acre\text{-}yr}$

where
- M = pounds of pollutant j generated per acre of land use i per year,
- P = annual precipitation, inches per year,
- PD_d = developed population density, persons per acre,
- α, β = factors given in table below,
- γ = street sweeping effectiveness factor, and
- $f_2(PD_d)$ = population density function.

Land Uses:
- i = 1 Residential
- i = 2 Commercial
- i = 3 Industrial
- i = 4 Other Developed, e.g., parks, cemeteries, schools (assume $PD_d = 0$)

Pollutants:
- j = 1 BOD_5, Total
- j = 2 Suspended Solids (SS)
- j = 3 Volatile Solids, Total (VS)
- j = 4 Total PO_4 (as PO_4)
- j = 5 Total N

Population Function:
- i = 1 $f_2(PD_d) = 0.142 + 0.218 \cdot PD_d^{0.54}$
- i = 2,3 $f_2(PD_d) = 1.0$
- i = 4 $f_2(PD_d) = 0.142$

Factors α and β for Equations: Separate factors, α, and combined factors, β, have units lb/acre-in. To convert to kg/ha-cm, multiply by 0.442.

		Pollutant, j				
	Land Use, i	1. BOD_5	2. SS	3. VS	4. PO_4	5. N
Separate Areas, α	1. Residential	0.799	16.3	9.45	0.0336	0.131
	2. Commercial	2.59	18.0	11.4	0.0612	0.239
	3. Industrial	0.994	23.8	11.8	0.0579	0.226
	4. Other	0.0969	2.31	2.23	0.00852	0.0519
Combined Areas, β	1. Residential	3.29	67.2	38.9	0.139	0.540
	2. Commercial	10.7	74.2	47.0	0.252	0.985
	3. Industrial	4.10	98.1	48.6	0.239	0.931
	4. Other	0.399	9.52	9.19	0.0351	0.214

Street Sweeping: Factor γ is a function of street sweeping interval, N_s, (days):

$$\gamma = \begin{cases} N_s/20 & \text{if } 0 \leq N_s \leq 20 \text{ days} \\ 1.0 & \text{if } N_s > 20 \text{ days} \end{cases}$$

TABLE 28. COMPARISON OF BOD LOADINGS

	BOD Loading	
	lb/ac-yr	kg/ha-yr
Separate Areas	21	24
Combined areas	88	99
Dry-Weather Flow*	621	697
DWF at 85% Treatment*	93	105

Assume residential land use; PD_d = 10 persons/acre (24.7 persons/ha) and P = 30 in/yr (76 cm/yr), and no influence of street sweeping (γ = 1).

* Assuming 0.17 lb-BOD/persons-day (0.08 kg-BOD/persons-day)

comparable to treatment plant effluent, although on a city-wide basis they would be greater because of higher loadings for commercial and industrial areas. Of course, BOD loads in both storm and combined sewage are in addition to the dry-weather flow loads since the usual BOD load for the latter of 0.17 lb/person-day (0.08 kg/person-day) is based upon measurement of flows actually received at treatment plants. The data from which the loadings shown in Table 24 were derived reflect discharges over and above those received by the plants.

4.6 Tabulation of Ontario BOD Loads and Runoffs

In order to minimize the volume of material presented for each city in the assessment, only BOD, PO_4, and N loadings were tabulated. The equations indicated in Table 27 may easily be used to calculate loadings of any of the desired parameters, given the precipitation and population density of the area of interest. As described in Section 4, land use variations are determined by first computing the fraction of undeveloped land in the urbanized area. The remaining land has a constant distribution of land uses, and can be used to weight the pollutant loadings factors to give an average over-all land use as follows:

$$\bar{M} = P \sum_{i=1}^{4} w_i \cdot a_1 \cdot f_{2_i}(PD) \cdot \gamma \qquad (51)$$

The land use distribution fractions for cities other than the nine test cities, w_i, are given below.

Land Use	Fraction, w_i
Residential	0.525
Commercial	0.103
Industrial	0.140
Open	0.232
	1.000

When equation (51) is applied to BOD loadings for separate areas, the result is:

$$\bar{M} = 0.419 \cdot P \cdot (0.142 + 0.218\ PD_d^{0.54}) + 0.409\ P \qquad (52)$$

where: $\bar{M}$ = average annual BOD loadings over four land uses, lb-BOD/ac-yr;

P = annual precipitation, inches; and

PD_d = developed population density, persons/acre.

For application to combined areas, the result is:

$$\bar{M} = 1.726 \cdot P \cdot (0.142 + 0.218\ PD_d^{0.54}) + 1.685\ P \qquad (53)$$

These composite equations may easily be applied over the non-test cities. Note that equation (53) is simply equation (52) multiplied by 4.12. Using equation (51) and Table 27, similar equations can be developed for total phosphate and total nitrogen. These parameters are important as far as pollution of the Great Lakes is concerned. Thus, for $T\text{-}PO_4$ in separate areas,

$$\bar{M} = 0.0176 \cdot P \cdot (0.142 + 0.218\ PD_d^{0.54}) + 0.0147\ P \qquad (54)$$

and for T-N in separate areas,

$$\bar{M} = 0.0688 \cdot P \cdot (0.142 + 0.218\ PD_d^{0.54}) + 0.0580\ P \qquad (55)$$

Equations (54) and (55) should be multiplied by 4.12 for combined area $T\text{-}PO_4$ and T-N loads, respectively.

Dry-weather flow loadings are computed simply on the basis of population density assuming average annual BOD generation of 0.17 lb/person-day (0.08 kg/person-day). Thus,

$$M_D = 62.1 \cdot PD_d \qquad (56)$$

where: M_D = average annual dry-weather flow BOD loading, lb-BOD/ac-yr.

Dry-weather loadings of total phosphate and total nitrogen may be found using data of Lager and Smith [46], which indicate that the average concentration of T-PO_4 (as PO_4) and T-N in dry-weather flow are 15 and 20 percent, respectively, of the BOD concentration. Thus, equation (56) may be multiplied by these percentages for calculation of T-PO_4 and T-N loadings.

Results of the analysis may be seen for each city in Tables 29, 30, 31, 32, 33 and 34. Area weighted averages for all areas are also shown. Owing to relatively low precipitation and relatively high population densities, dry-weather pollutant loads are generally higher than corresponding wet-weather values. However, as seen previously in Table 28, if 85 percent treatment is assumed for dry-weather loads, the resulting values are comparable to storm and combined sewered loads.

4.7 List of Variables

a	Value of function $f_2(PD_d)$ when $PD_d = 0$
A_i	Area of land use i
AR	Wet-weather runoff, depth/time
α	Normalized loading factor for separate sewered areas, mass/area-time-length
b	Coefficient in function $f_2(PD_d)$
BOD	Biochemical oxygen demand
BOD_5	Biochemical oxygen demand at five days
β	Normalized loading factor for combined sewered areas, mass/area-time-length
C	Concentration, mass pollutant/total mass
COD	Chemical oxygen demand
com	Abbreviation for commercial
CR	Runoff coefficient
DD	Dust and dirt
dd_i	Dust and dirt loading factor for land use i, mass/time-curb-length

DWF	Abbreviation for dry-weather flow and dry-weather flow runoff, depth/time
$f_1(P)$	Factor for adjustment of pollutant loads, a function of precipitation
$f_2(PD_d)$	Factor for adjustment of pollutant loads, a function of population density
$F_{i,j}$	Fraction of dust and dirt or land use L that is pollutant p
$G_{L,i}$	Length of curb per area of land use L
γ	Street sweeping factor
I	Imperviousness as a fraction or percent
I_a	Initial abstraction (loss) from precipitation, depth
K	Factor to convert runoff times concentration to pollutant loadings
m	Exponent in function $f_2(PD_d)$
M	Pollutant loading, mass/area-time
$\overline{M}$	Pollutant loading averaged over different land uses, mass/area-time
M_c	Pollutant loading in combined sewered areas, mass/area-time
M_D	Pollutant loading under dry-weather conditions, mass/area-time
M_s	Pollutant loading in separate sewered areas, mass/area-time
n	Number of storms per year
N	Nitrogen
N_D	Number of dry days preceding a storm
N_s	Street sweeping interval, days
P	Precipitation rate, depth/time
P_o	Mass of pollutant on surface at end of previous storm, mass
$P_{i,j}$	Mass of pollutants on surface of land use L at beginning of storm, mass
P_s	Precipitation depth during one storm, length
PD	Population density, persons/acre
PD_d	Developed population density, persons/acre
PO_4	Phosphate or total phosphate
r	Correlation coefficient
res	Abbreviation for residential
ρ	Water density, mass/volume

SS	Suspended solids
TOC	Total organic carbon
TPO_4	Total phosphate
TS	Total solids
VS	Volatile solids
w_i	Fraction of total area that is land use i

TABLE 29. DRY WEATHER BOD LOADINGS

NO	URBANIZED AREA	ANNL PRECP IN/YR	DRY WEATHER BOD (LBS/ACRE-YEAR) COMB	STORM	UNSEW	AVER
1	AJAX	33	1840.	738.	198.	518.
2	AURORA	31	0.	742.	232.	419.
3	BARRIE	32	0.	977.	199.	498.
4	BELLEVILLE	34	1418.	551.	274.	579.
5	BRAMPTON	31	0.	680.	356.	629.
6	BRANTFORD	32	0.	681.	355.	614.
7	BURLINGTON	32	0.	788.	289.	576.
8	CHATHAM	30	998.	497.	354.	602.
9	CHINGUACOUSY	31	0.	812.	328.	790.
10	COBOURG	34	0.	980.	199.	500.
11	DUNDAS	32	0.	1050.	197.	541.
12	ETOBICOKE	31	0.	804.	318.	724.
13	GALT	33	0.	1033.	197.	529.
14	GEORGETOWN	32	0.	1084.	198.	564.
15	GUELPH	33	0.	928.	218.	543.
16	HAMILTON	32	990.	378.	0.	843.
17	KINGSTON	35	1396.	550.	0.	778.
18	KITCH.-WATERLOO	34	0.	806.	299.	612.
19	LEAMINGTON	30	2098.	720.	197.	550.
20	LINDSAY	33	0.	938.	201.	480.
21	LONDON	37	1794.	613.	368.	610.
22	MARKAM	31	1061.	808.	208.	454.
23	MIDLAND	38	985.	596.	202.	475.
24	MISSISSAUGA	31	0.	785.	303.	598.
25	NEWMARKET	31	0.	808.	318.	434.
26	NIAGRA FALLS	33	879.	378.	273.	573.
27	NORTH BAY	35	1992.	749.	327.	782.
28	OAKVILLE	31	0.	838.	273.	561.
29	ORILLIA	36	0.	1004.	198.	513.
30	OSHAWA	34	0.	681.	355.	613.
31	OWEN SOUND	35	1268.	554.	204.	468.
32	PETERBOROUGH	32	0.	1073.	198.	556.
33	PICKERING	31	0.	968.	200.	494.
34	PORT COLBOURNE	34	0.	944.	201.	483.
35	PORT ERIE	34	2272.	709.	198.	576.
36	PRESTON	34	0.	984.	199.	502.
37	RICHMOND HILL	31	0.	864.	209.	451.
38	ST. CATHARINES	32	927.	471.	355.	607.
39	ST. THOMAS	35	1322.	402.	198.	570.
40	SARINA	34	1779.	543.	0.	864.
41	SLT. STE. MARIE	37	0.	800.	252.	515.
42	SCARBOROUGH	31	1823.	558.	326.	777.
43	SIMCOE	35	1958.	729.	197.	532.
44	STRATFORD	38	0.	1046.	197.	538.
45	SUDBURY	32	0.	813.	265.	495.
46	THUNDER BAY	28	1370.	565.	313.	620.
47	TORONTO	31	2177.	888.	0.	1855.
48	TRENTON	33	0.	1096.	198.	573.
49	WALLACEBURG	30	1637.	615.	198.	507.
50	WELLAND	34	1560.	552.	198.	514.
51	WHITBY	34	0.	972.	198.	496.
52	WINDSOR	30	1586.	559.	276.	652.
53	WOODSTOCK	34	0.	1010.	198.	516.
54	YORK	31	1808.	614.	0.	1617.
55	YORK, EAST	31	1715.	546.	0.	1283.
56	YORK, NORTH	31	0.	434.	0.	834.
	WEIGHTED AVE.	32.75	1545.	736.	255.	743.

TABLE 30. WET WEATHER BOD LOADINGS

NO	URBANIZED AREA	ANNL. PRECP IN/YR	WET WEATHER BOD (LBS/ACRE-YEAR) COMB	STORM	UNSEW	AVER
1	AJAX	33	141.2	26.9	21.1	34.6
2	AURORA	31	0.0	25.3	20.3	22.2
3	BARRIE	32	0.0	28.0	20.5	23.4
4	BELLEVILLE	34	135.0	26.0	22.9	44.3
5	BRAMPTON	31	0.0	24.8	21.8	24.4
6	BRANTFORD	32	0.0	25.7	22.5	25.0
7	BURLINGTON	32	0.0	19.5	14.5	17.4
8	CHATHAM	30	108.6	22.5	21.1	46.2
9	CHINGUACOUSY	31	0.0	25.9	21.5	25.7
10	COBOURG	34	0.0	29.7	21.8	24.8
11	DUNDAS	32	0.0	28.5	20.5	23.7
12	ETOBICOKE	31	0.0	25.8	21.4	25.1
13	GALT	33	0.0	29.2	21.1	24.3
14	GEORGETOWN	32	0.0	28.7	20.5	23.9
15	GUELPH	33	0.0	23.6	16.8	19.9
16	HAMILTON	32	115.6	22.8	0.0	93.3
17	KINGSTON	35	93.9	17.8	0.0	38.4
18	KITCH.-WATERLOO	34	0.0	21.3	17.4	19.8
19	LEAMINGTON	30	135.6	24.4	19.2	52.4
20	LINDSAY	33	0.0	28.5	21.2	24.0
21	LONDON	37	157.2	29.0	24.7	44.0
22	MARKAM	31	114.0	25.9	20.0	30.6
23	MIDLAND	38	137.1	27.3	24.4	62.6
24	MISSISSAUGA	31	0.0	25.7	21.2	23.9
25	NEWMARKET	31	0.0	25.9	20.1	23.2
26	NIAGRA FALLS	35	111.7	25.5	24.5	38.8
27	NORTH BAY	35	153.4	28.7	24.2	54.0
28	OAKVILLE	31	0.0	26.1	20.8	23.5
29	ORILLIA	36	0.0	31.7	23.0	26.4
30	OSHAWA	34	0.0	27.3	22.9	26.3
31	OWEN SOUND	35	134.8	26.8	20.5	44.3
32	PETERBOROUGH	32	0.0	26.6	20.5	23.8
33	PICKERING	31	0.0	27.0	19.9	22.6
34	PORT COLBORNE	34	0.0	29.5	21.8	24.7
35	PORT ERIE	34	155.1	27.5	21.8	37.5
36	PRESTON	34	0.0	29.8	21.8	24.9
37	RICHMOND HILL	31	0.0	26.3	20.0	22.4
38	ST. CATHARINES	32	101.9	20.3	18.8	48.9
39	ST. THOMAS	35	136.3	25.2	22.4	58.2
40	SARINA	34	144.1	26.0	0.0	56.7
41	SLT. STE. MARIE	37	0.0	34.0	26.9	30.3
42	SCARBOROUGH	31	132.3	23.8	21.5	43.8
43	SIMCOE	35	152.6	28.5	24.3	37.2
44	STRATFORD	38	0.0	33.8	24.3	28.1
45	SUDBURY	32	0.0	26.7	21.4	23.6
46	THUNDER BAY	28	135.5	28.0	25.9	45.6
47	TORONTO	31	178.3	35.0	0.0	142.5
48	TRENTON	33	0.0	29.7	21.1	24.7
49	WALLACEBURG	30	124.1	23.5	19.2	45.3
50	WELLAND	34	138.7	26.1	21.7	46.2
51	WHITBY	34	0.0	29.7	21.8	24.8
52	WINDSOR	30	115.8	21.3	18.5	38.6
53	WOODSTOCK	34	0.0	30.0	21.7	25.0
54	YORK	31	132.0	24.3	0.0	114.7
55	YORK, EAST	31	129.9	23.7	0.0	90.6
56	YORK, NORTH	31	0.0	26.1	0.0	26.1
	WEIGHTED AVE.	32.75	137.0	25.7	21.3	44.5

TABLE 31. DRY WEATHER T-PO_4 LOADINGS

NO	URBANIZED AREA	ANNL PRECP IN/YR	DRY WEATHER PO4 (LBS/ACRE-YEAR) COMB	STORM	UNSEW	AVER
1	AJAX	33	276.1	110.7	29.7	77.7
2	AURORA	31	0.0	111.3	34.9	62.8
3	BARRIE	32	0.0	146.6	29.9	74.8
4	BELLEVILLE	34	212.8	82.7	41.1	86.9
5	BRAMPTON	31	0.0	102.0	53.5	94.4
6	BRANTFORD	32	0.0	102.2	53.2	92.1
7	BURLINGTON	32	0.0	116.3	43.3	86.5
8	CHATHAM	30	149.8	74.6	53.1	90.4
9	CHINGUACOUSY	31	0.0	121.9	49.2	118.5
10	COBOURG	34	0.0	147.1	29.9	75.0
11	DUNDAS	32	0.0	157.6	29.6	81.1
12	ETOBICOKE	31	0.0	120.7	47.8	108.7
13	GALT	33	0.0	155.0	29.6	79.5
14	GEORGETOWN	32	0.0	152.7	29.7	84.6
15	GUELPH	33	0.0	139.3	32.7	81.4
16	HAMILTON	32	148.6	56.8	0.0	126.6
17	KINGSTON	35	209.5	82.5	0.0	116.8
18	KITCH.-WATERLOO	34	0.0	121.0	44.8	91.8
19	LEAMINGTON	30	314.9	108.0	29.6	82.5
20	LINDSAY	33	0.0	140.8	30.2	72.0
21	LONDON	37	264.6	92.0	39.0	91.6
22	MARKAM	31	159.3	121.3	31.3	68.1
23	MIDLAND	38	147.9	59.5	30.4	71.3
24	MISSISSAUGA	31	0.0	117.8	45.4	89.7
25	NEWMARKET	31	0.0	121.5	32.7	65.2
26	NIAGRA FALLS	33	131.9	56.7	41.0	86.1
27	NORTH BAY	35	298.9	112.4	49.0	117.3
28	OAKVILLE	31	0.0	125.8	40.9	84.2
29	ORILLIA	36	0.0	150.7	29.7	77.0
30	OSHAWA	34	0.0	102.3	53.2	92.0
31	OWEN SOUND	35	190.3	83.2	30.6	70.3
32	PETERBOROUGH	32	0.0	161.0	29.6	83.5
33	PICKERING	31	0.0	145.3	29.9	74.1
34	PORT COLBOURNE	34	0.0	141.7	30.2	72.4
35	PORT ERIE	34	341.0	106.4	29.7	86.4
36	PRESTON	34	0.0	147.7	29.8	75.3
37	RICHMOND HILL	31	0.0	129.6	31.4	67.7
38	ST. CATHARINES	32	139.1	70.7	53.3	91.0
39	ST. THOMAS	35	198.4	60.4	29.7	85.5
40	SARINA	34	267.0	81.5	0.0	129.7
41	SLT. STE. MARIE	37	0.0	120.1	37.8	77.3
42	SCARBOROUGH	31	273.7	83.7	48.9	116.6
43	SIMCOE	35	293.8	109.4	29.6	79.8
44	STRATFORD	38	0.0	156.9	29.6	80.7
45	SUDBURY	32	0.0	122.0	39.7	74.3
46	THUNDER BAY	28	205.6	84.8	47.0	93.1
47	TORONTO	31	326.7	135.3	0.0	278.4
48	TRENTON	33	0.0	164.6	29.7	86.0
49	WALLACEBURG	30	243.7	96.3	29.8	76.1
50	WELLAND	34	234.1	82.9	29.7	77.1
51	WHITBY	34	0.0	145.8	29.9	74.4
52	WINDSOR	30	238.1	83.8	41.4	97.9
53	WOODSTOCK	34	0.0	151.6	29.7	77.5
54	YORK	31	271.5	92.1	0.0	242.7
55	YORK, EAST	31	257.4	82.0	0.0	192.5
56	YORK, NORTH	31	0.0	125.1	0.0	125.1
	WEIGHTED AVE.	32.75	231.9	110.4	38.2	111.5

TABLE 32. WET WEATHER T-PO_4 LOADINGS

NO	URBANIZED AREA	ANNL. PRECP IN/YR	WET WEATHER PO4 (LBS/ACRE-YEAR) COMB	STORM	UNSEW	AVER
1	AJAX	33	5.6	1.1	0.8	1.3
2	AURORA	31	0.0	1.0	0.8	0.9
3	BARRIE	32	0.0	1.1	0.8	0.9
4	BELLEVILLE	34	5.3	1.0	0.9	1.7
5	BRAMPTON	31	0.0	1.0	0.8	0.9
6	BRANTFORD	32	0.0	1.0	0.9	1.0
7	BURLINGTON	32	0.0	0.8	0.6	0.7
8	CHATHAM	30	4.3	0.9	0.8	1.8
9	CHINGUACOUSY	31	0.0	1.0	0.8	0.9
10	COBOURG	34	0.0	1.2	0.8	1.0
11	DUNDAS	32	0.0	1.1	0.8	0.9
12	ETOBICOKE	31	0.0	1.0	0.8	0.9
13	GALT	33	0.0	1.1	0.8	0.9
14	GEORGETOWN	32	0.0	1.1	0.8	0.9
15	GUELPH	33	0.0	1.0	0.7	0.8
16	HAMILTON	32	4.5	0.9	0.7	1.7
17	KINGSTON	35	3.8	0.7	0.7	1.5
18	KITCH.-WATERLOO	34	0.0	0.9	0.7	0.8
19	LEAMINGTON	30	5.3	0.9	0.7	1.3
20	LINDSAY	33	0.0	1.1	0.8	0.9
21	LONDON	37	6.2	1.1	0.9	1.7
22	MARKAM	31	4.5	1.0	0.8	1.2
23	MIDLAND	38	5.4	1.1	0.9	1.4
24	MISSISSAUGA	31	0.0	1.0	0.8	0.9
25	NEWMARKET	33	0.0	1.0	0.8	0.9
26	NIAGRA FALLS	33	4.5	0.9	0.8	2.7
27	NORTH BAY	35	6.1	1.1	0.9	1.3
28	OAKVILLE	31	0.0	1.0	0.8	0.9
29	ORILLIA	36	0.0	1.2	0.9	1.0
30	OSHAWA	34	0.0	1.1	0.9	1.0
31	OWEN SOUND	35	5.3	1.0	0.9	1.7
32	PETERBOROUGH	32	0.0	1.1	0.8	0.9
33	PICKERING	31	0.0	1.2	0.8	0.9
34	PORT COLBURNE	34	0.0	1.2	0.8	1.0
35	PORT ERIE	34	6.2	1.1	0.8	1.5
36	PRESTON	34	0.0	1.2	0.8	1.0
37	RICHMOND HILL	31	0.0	1.0	0.8	0.9
38	ST. CATHARINES	32	4.1	0.8	0.8	2.0
39	ST. THOMAS	35	5.4	1.0	0.9	2.3
40	SARINA	34	5.7	1.0	0.9	2.2
41	SLT. STE. MARIE	37	0.0	1.5	1.2	1.3
42	SCARBOROUGH	31	5.2	0.9	0.8	1.7
43	SIMCOE	35	6.1	1.1	0.9	1.4
44	STRATFORD	38	0.0	1.3	0.9	1.1
45	SUDBURY	32	0.0	1.0	0.8	0.9
46	THUNDER BAY	28	5.0	1.0	0.8	1.7
47	TORONTO	31	6.6	1.3	0.8	5.3
48	TRENTON	33	0.0	1.2	0.8	1.0
49	WALLACEBURG	30	4.9	0.9	0.7	1.4
50	WELLAND	34	5.5	1.0	0.8	1.7
51	WHITBY	34	0.0	1.2	0.8	1.0
52	WINDSOR	30	4.7	0.9	0.7	1.5
53	WOODSTOCK	34	0.0	1.2	0.8	1.0
54	YORK	31	5.2	0.9	0.0	4.5
55	YORK, EAST	31	5.1	0.9	0.0	3.6
56	YORK, NORTH	31	0.0	1.0	0.0	1.0
	WEIGHTED AVE.	32.75	5.3	1.0	0.8	1.7

TABLE 33. DRY WEATHER T-N LOADINGS

NO	URBANIZED AREA	ANNL. PRECP IN/YR	DRY WEATHER NIT (LBS/ACRE-YEAR) COMB	STORM	UNSEW	AVER
1	AJAX	33	367.3	147.3	39.5	103.4
2	AURORA	31	0.0	148.1	46.4	83.6
3	BARRIE	32	0.0	195.1	39.7	96.5
4	BELLEVILLE	34	283.2	110.1	54.7	115.7
5	BRAMPTON	31	0.0	135.7	71.1	125.5
6	BRANTFORD	32	0.0	136.0	70.8	122.5
7	BURLINGTON	32	0.0	157.4	57.6	115.1
8	CHATHAM	30	199.3	99.3	70.6	120.3
9	CHINGUACOUSY	31	0.0	162.2	65.4	157.6
10	COBOURG	34	0.0	195.6	39.7	99.8
11	DUNDAS	32	0.0	209.7	39.4	108.0
12	ETOBICOKE	31	0.0	160.5	63.6	144.6
13	GALT	33	0.0	206.2	39.4	105.7
14	GEORGETOWN	32	0.0	216.4	39.5	112.6
15	GUELPH	33	0.0	185.4	43.5	108.3
16	HAMILTON	32	197.7	75.5	0.0	168.4
17	KINGSTON	35	278.6	109.7	0.0	155.4
18	KITCH.-WATERLOO	34	0.0	161.0	59.7	122.2
19	LEAMINGTON	30	419.0	143.7	39.4	109.8
20	LINDSAY	33	0.0	187.4	40.2	95.8
21	LONDON	37	358.2	122.4	51.9	121.9
22	MARKAM	31	211.5	161.4	41.6	90.6
23	MIDLAND	38	196.8	79.1	40.4	94.8
24	MISSISSAUGA	31	0.0	156.7	60.4	119.4
25	NEWMARKET	31	0.0	161.4	43.6	86.7
26	NIAGRA FALLS	33	175.5	75.4	54.6	114.5
27	NORTH BAY	35	397.7	149.6	65.2	156.1
28	OAKVILLE	31	0.0	167.4	54.4	112.1
29	ORILLIA	36	0.0	200.5	39.5	102.4
30	OSHAWA	34	0.0	136.0	70.8	122.5
31	OWEN SOUND	35	253.2	110.7	40.7	93.5
32	PETERBOROUGH	32	0.0	214.3	39.4	111.0
33	PICKERING	31	0.0	193.3	39.8	98.6
34	PORT COLBOURNE	34	0.0	188.6	40.1	96.4
35	PORT ERIE	34	453.7	141.5	39.6	114.9
36	PRESTON	34	0.0	196.5	39.7	100.2
37	RICHMOND HILL	31	0.0	172.5	41.8	90.1
38	ST. CATHARINES	32	185.0	94.1	70.9	121.1
39	ST. THOMAS	35	264.0	80.3	39.5	113.8
40	SARINA	34	355.3	108.4	0.0	172.6
41	SLT. STE. MARIE	37	0.0	159.8	50.2	102.8
42	SCARBOROUGH	31	364.1	111.3	65.1	155.2
43	SIMCOE	35	390.9	145.6	39.4	106.2
44	STRATFORD	38	0.0	208.8	39.4	107.4
45	SUDBURY	32	0.0	162.3	52.9	98.9
46	THUNDER BAY	28	273.6	112.8	62.5	123.8
47	TORONTO	31	434.7	177.3	0.0	370.3
48	TRENTON	33	0.0	218.9	39.6	114.4
49	WALLACEBURG	30	326.9	122.6	39.6	101.2
50	WELLAND	34	311.5	110.3	39.5	102.6
51	WHITBY	34	0.0	194.0	39.8	99.0
52	WINDSOR	30	316.7	111.6	55.0	130.2
53	WOODSTOCK	34	0.0	201.7	39.5	103.1
54	YORK	31	341.0	122.6	0.0	322.8
55	YORK, EAST	31	342.4	109.1	0.0	256.1
56	YORK, NORTH	31	0.0	166.4	0.0	166.4
	WEIGHTED AVE.	32.75	309.0	146.9	50.9	148.4

TABLE 34. WET WEATHER T-N LOADINGS

NO	URBANIZED AREA	ANNL. PRECP IN/YR	WET WEATHER NIT (LBS/ACRE-YEAR) COMB	STORM	UNSEW	AVER
1	AJAX	33	21.9	4.1	3.2	5.3
2	AURORA	31	0.0	3.9	0.0	3.3
3	BARRIE	32	0.0	4.3	1.1	3.5
4	BELLEVILLE	34	20.9	4.0	4.4	6.8
5	BRAMPTON	31	0.0	3.8	3.1	3.7
6	BRANTFORD	32	0.0	3.9	4.4	3.8
7	BURLINGTON	32	0.0	4.1	2.2	3.7
8	CHATHAM	30	16.7	4.4	2.2	7.1
9	CHINGUACOUSY	31	0.0	4.0	3.3	3.9
10	COBOURG	34	0.0	4.6	3.3	3.8
11	DUNDAS	32	0.0	4.4	1.1	3.6
12	ETOBICOKE	31	0.0	4.0	2.2	3.8
13	GALT	33	0.0	4.5	2.2	3.7
14	GEORGETOWN	32	0.0	4.4	1.1	3.6
15	GUELPH	33	0.0	4.9	3.3	3.8
16	HAMILTON	32	17.7	4.4	0.0	14.3
17	KINGSTON	35	14.9	4.8	2.2	8.1
18	KITCH.-WATERLOO	34	0.0	4.5	2.2	3.3
19	LEAMINGTON	30	20.8	4.7	4.9	8.0
20	LINDSAY	33	0.0	4.4	2.2	3.6
21	LONDON	37	24.4	4.4	4.7	8.6
22	MARKAM	31	17.5	4.0	0.0	6.6
23	MIDLAND	38	21.0	4.1	4.7	8.6
24	MISSISSAUGA	31	0.0	3.9	2.2	3.6
25	NEWMARKET	31	0.0	4.0	2.2	3.6
26	NIAGRA FALLS	33	17.7	4.5	1.1	4.4
27	NORTH BAY	35	23.8	4.4	4.7	8.3
28	OAKVILLE	31	0.0	4.0	1.1	3.6
29	ORILLIA	36	0.0	4.9	4.4	4.0
30	OSHAWA	34	0.0	4.6	4.4	4.0
31	OWEN SOUND	35	20.8	4.4	4.4	8.8
32	PETERBOROUGH	32	0.0	4.4	1.1	3.6
33	PICKERING	31	0.0	4.1	0.0	3.4
34	PORT COLBOURNE	34	0.0	4.5	3.3	3.7
35	PORT ERIE	34	24.2	4.2	3.3	5.7
36	PRESTON	34	0.0	4.6	3.3	3.8
37	RICHMOND HILL	31	0.0	4.0	0.0	3.4
38	ST. CATHARINES	32	16.2	4.2	0.0	7.7
39	ST. THOMAS	35	21.0	4.8	4.4	8.9
40	SARINA	34	22.3	4.9	0.0	8.7
41	SLT. STE. MARIE	37	0.0	4.8	4.4	5.2
42	SCARBOROUGH	31	20.5	4.6	2.2	8.7
43	SIMCOE	35	23.7	4.4	4.4	5.7
44	STRATFORD	38	0.0	5.2	6.6	4.3
45	SUDBURY	32	0.0	4.1	2.2	3.6
46	THUNDER BAY	28	19.5	4.9	6.6	6.5
47	TORONTO	31	25.9	4.9	2.2	7.7
48	TRENTON	33	0.0	4.6	2.2	3.7
49	WALLACEBURG	30	19.2	4.6	4.4	7.4
50	WELLAND	34	21.5	4.0	3.3	6.6
51	WHITBY	34	0.0	4.6	3.3	3.8
52	WINDSOR	30	18.3	4.3	3.9	8.1
53	WOODSTOCK	34	0.0	4.6	3.3	3.8
54	YORK	31	20.5	4.7	0.0	17.8
55	YORK, EAST	31	20.1	4.6	0.0	14.0
56	YORK, NORTH	31	0.0	4.0	0.0	4.0
	WEIGHTED AVE.	32.75	20.8	3.9	3.2	6.8

5. OVERALL COST ASSESSMENT

This section develops and applies a methodology to estimate the cost of controlling pollution from storm water discharges province wide. Costs of controlling combined sewer overflows, storm water runoff, and/or providing tertiary treatment are compared. A general methodology for determining wet-weather pollution control costs is presented. Then, a procedure is described for determining the relationship between storage, treatment, and pollutant control for control of wet-weather flows. Generalized predictive equations are developed based on relatively intensive studies of four cities: Burlington, Kingston, St. Catharines, and Sault Ste. Marie. Knowing this "production function" one can determine the optimum combination of storage and treatment, by combining this information with data on the cost and performance of the available control options. This information is combined to produce the Ontario assessment. Results are presented for all cities $\geq$ 10,000 persons. Related reports describing this methodology are available [62, 63].

5.1 Methodology

5.1.1 Principles

There are several economic theories which, when applied to environmental resources management, assist in the decision-making process. One such theory is production theory, which provides techniques that aid in evaluating items such as the optimum size of a reservoir for water supply and flood control, or a wastewater treatment plant for pollution control. When the cost of inputs such as the reservoir or treatment plant is known, the cost of achieving a desired level of output (e.g., water supply or pollution control) may be determined.

In storm water management, the inputs are usually in the form of a storage capacity and a treatment rate. Storage is expressed in terms of million gallons or inches over a certain area, typically the watershed being analyzed. The unit for treatment is either million gallons per day or inches per hour, using the same area as storage.

When the degree of wet-weather control is considered as a single output, it can be expressed either in terms of the percent of the runoff treated or the number of overflows per year. This is with respect to

quantity only and is, therefore, dependent upon the input storage capacity and treatment rate.

When dealing with only two inputs it is feasible to use a graphical method to find the optimum combinations. Isoquants can be constructed which represent equal levels of output for different combinations of input (see Figure 14). For example, each isoquant could represent a specific percent of the runoff treated for different combinations of storage and treatment. Isoquants have the following properties [48]:

1) Two isoquants cannot intersect. Intersecting isoquants would imply two different levels of output from the same input.
2) Isoquants slope downward and to the right because as one input increases it takes less of the other input to achieve the same level of output
3) Isoquants are convex to the origin because of the decreasing ability of one input to be substituted for another to obtain a given level of output. This is known as the principle of diminishing marginal rate of substitution.

Also on Figure 14, a series of parallel lines have been constructed. These lines represent combinations of input 1 and input 2 which may be achieved at the same total cost. The lines are known as isocost lines. The slope of the isocost lines is the relative unit cost between input 1 and input 2. The most economical combination of input 1 and input 2 to produce a desired level of output is the point where the isocost lines become tangent to the isoquant representing the desired level of output.

The line which joins the points of tangency among several isoquants and the isocost lines is called the expansion path. After the expansion path has been determined, the optimum combination of inputs can be determined for any level of output by finding the intersection of the isoquant representing the desired level of output and the expansion path.

The maximum output for a given cost may be found by constructing the isocost line for the given total expenditure. The slope of the isocost line is the relative unit cost of the two inputs. The intercept of the axis depicting input 1 would be the allowed total cost divided by

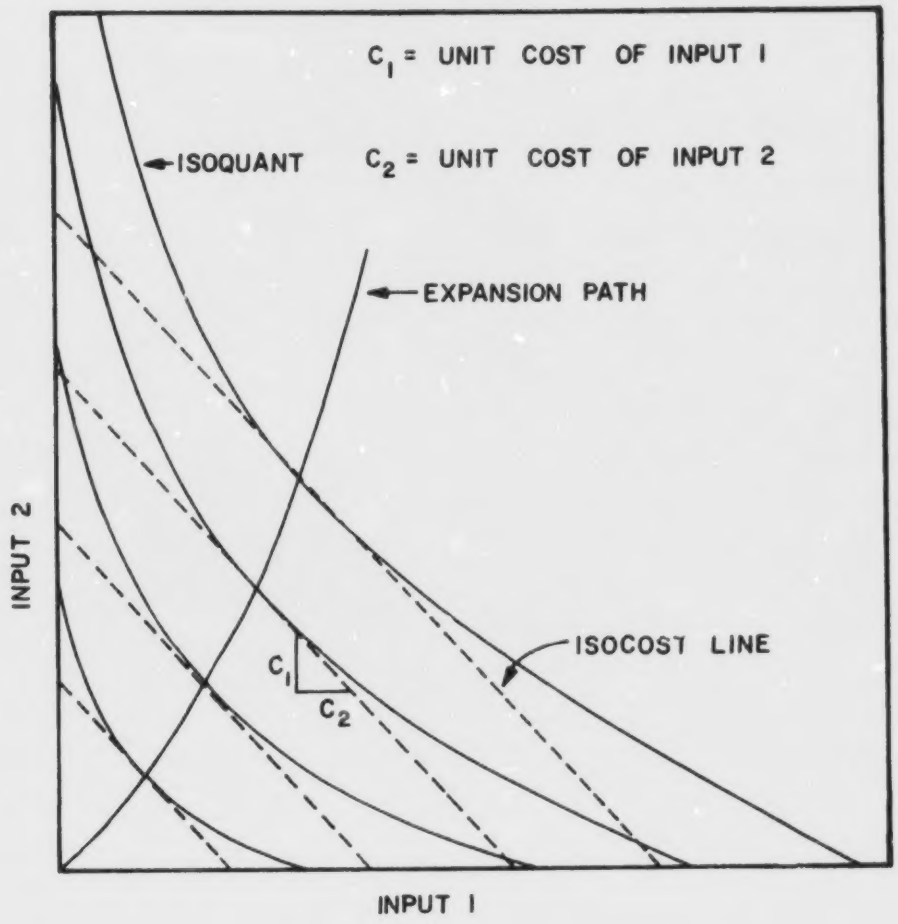


FIGURE 14. DETERMINATIONS OF LEAST COST COMBINATION OF INPUTS.

the unit cost of input 1. From this information, the isocost line may be drawn. The point where the isocost line intersects the expansion path gives the combination of inputs which produces the maximum output at the given cost.

The storm water quality management problem can be expressed in the more compact mathematical form shown below:

minimize

$$Z = c_S(S) + c_T(T) \tag{57}$$

subject to

$$f(R_1;S,T) = 0$$

$$R_1;S,T \geq 0$$

where: Z = total control costs,
$c_S(S)$ = storage costs,
$c_T(T)$ = treatment costs,
S = storage volume,
T = treatment rate,
R_1 = percent pollutant control, and
$f(R_1;S,T)$ = production function relating the level of pollutant control attainable with specified availabilities of storage (S) and treatment (T).

The next three sections describe:

- the available storage/treatment options - their costs and effectiveness;
- the production functions for evaluating tradeoffs between storage and treatment; and
- the solution to the optimization problem yielding the optimum expansion path for any city.

Given this information, the final assessment is presented.

5.1.2 Control technology and associated costs

A wide variety of control alternatives is available for improving the quality of wet-weather flows [49, 50, 51]. Rooftop and parking lot storage, surface and underground tanks and storage in treatment units

are the flow attenuation control alternatives. Wet-weather quality control alternatives can be subdivided into two categories: primary devices and secondary devices. Primary devices take advantage of physical processes such as screening, settling, and flotation. Secondary devices take advantage of biological processes and physical-chemical processes. These control devices are suitable for treating storm water runoff as well as combined sewer overflows. However, the contact stabilization process is feasible only if the existing sewage treatment plant is of an activated sludge type. The quantities of wet-weather flows that can be treated by this process are limited by the amount of excess activated sludge available from the dry-weather plant.

At the present time, there are several installations throughout the U.S. designed to evaluate the effectiveness of various primary and secondary devices. A summary of the design criteria and performance of these devices is presented in Table 35. Based on these data, the representative performance of primary devices is assumed to be 40 percent BOD_5 removal efficiency, and that of secondary devices to be 85 percent BOD_5 removal efficiency.

"Storage" devices will typically be used in conjunction with the above "treatment" devices. The two purposes are interrelated. Wastewater detained a sufficient time in a storage unit will undergo treatment. On the other hand, treatment units also function as storage units in that they equalize fluctuations in influent flow and concentration. DiToro presents approaches for evaluating the equalization and treatment which occurs in both of these units [52]. The STORM model, which was used in this assessment, assumes the configuration for storage and treatment shown in Figure 15. No treatment is assumed to occur in storage, and "treatment" is assumed to be complete removal of all pollutants routed through treatment. Thus, for the purpose of this assessment, no treatment is assumed to occur in storage and control costs are assigned accordingly. This assumption tends to underestimate the costs of storage since all provisions for solids handling are included in treatment.

5.2 Cost of treatment and storage

Cost data for installed wet-weather treatment devices are listed in Table 36. Since wet-weather control facilities operate

TABLE 35. WET-WEATHER TREATMENT PLANT PERFORMANCE DATA

Device	Control Alternatives	Design Criteria gpm/ft^2	Design Criteria (l/min-m^2)	Reported BOD_5 Removal Efficiency, η
Primary	Swirl Concentrator[a,b]	60.0	(2,448.0)	0.25 – 0.50
	Microstrainer[c]	20.0	(816.0)	0.40 – 0.60
	Dissolved Air Flotation w/ Chemical Addition[d]	2.5	(102.0)	0.50 – 0.60
	Sedimentation[e]	0.5	(20.4)	0.25 – 0.40
	Representative Performance			0.40
Secondary	Contact Stabilization[f]	Cont 0.25 hours Stab 3.00 hours		0.75 – 0.88
	Physical-Chemical[g]	3.00 hours		0.85 – 0.95
	Representative Performance			0.85

[a]Field and Moffa [53]

[b]APWA [54]

[c]Maher [55]

[d]Lager and Smith [46]

[e]Performance data based on domestic wastewater treatment.

[f]Agnew et al [56]

[g]Estimate based on performance of these units for domestic wastewater.

TABLE 36. INSTALLED COSTS FOR WET-WEATHER TREATMENT DEVICES

Control Device	Capacity mgd	Capacity (m^3/day)	Annual Cost per mgd:[h] (m^3/day) $/yr Amortized Capital[a,b] per mgd	Amortized Capital[a,b] (m^3/day)	Operation and Maintenance per mgd	Operation and Maintenance (m^3/day)	Total mgd	Total ($10^6 m^3$/day)
Swirl Concentrator[c]	8.9	(34,500)	5,600	(1.48)	2,100	(0.55)	7,700	(29.6)
Microstrainer[d]	7.4	(28,700)	14,230	(3.76)	3,895	(1.03)	18,125	(8.6)
Dissolved Air Flotation[e]	25.0	(96,900)	71,706	(18.94)	16,700	(4.41)	88,406	(33.5)
Contact Stabilization[g]	20.0	(77,500)	120,000	(31.70)	24,000	(6.34)	144,000	(54.4)

[a]Based on 8% interest for 20 years.

[b]Construction cost; does not include sludge handling costs.

[c]Field and Moffa [53]

[d]Maher [55]

[e]Lager and Smith [46] for Racine, Wisconsin adjusted to ENR = 2,200.

[f]Operation and maintenance costs based on 480 hours of operation @ $0.341/1000 gallons ($0.0126 per 1000 litres).

[g]Agnew et al [56]. Operation and maintenance costs based on 960 hours of operation.

[h]All gallons are U.S. All costs are U.S. dollars.

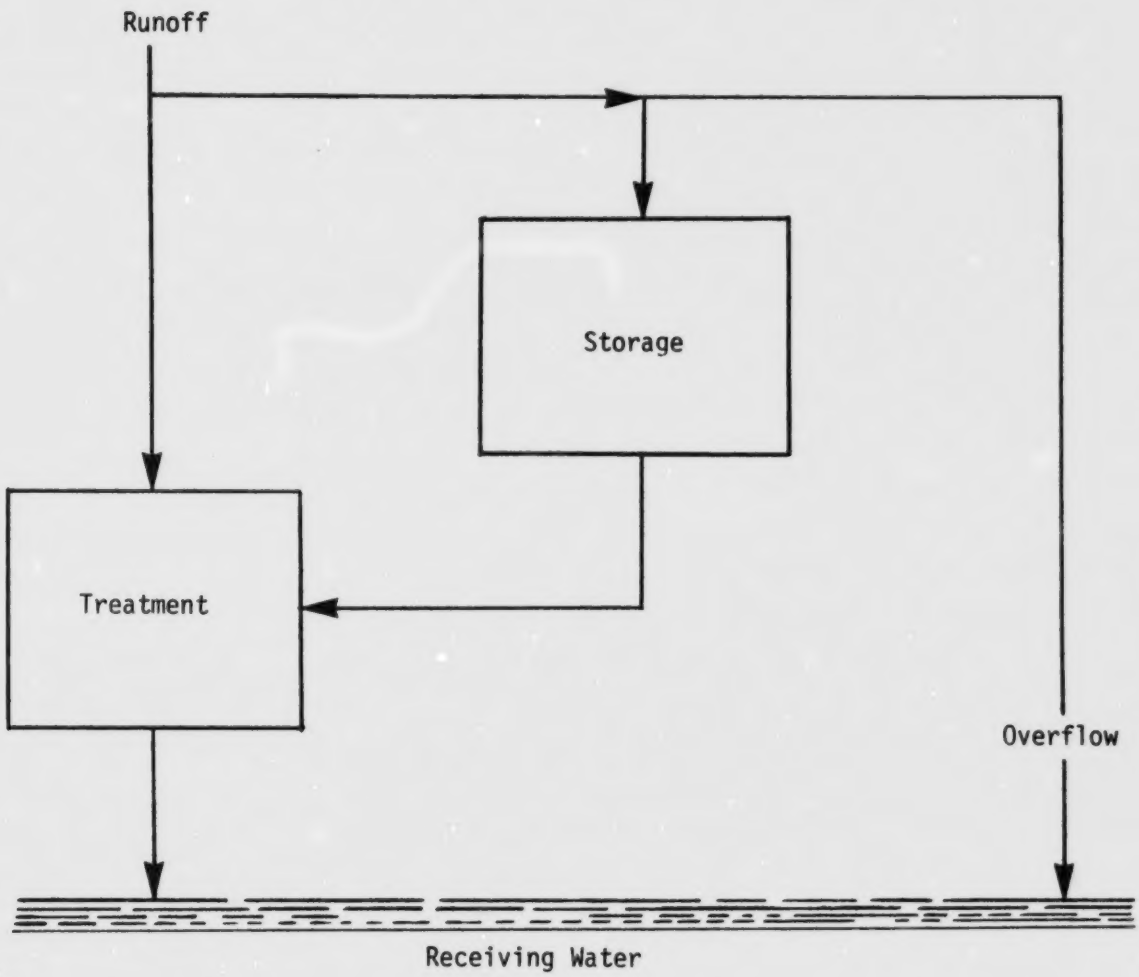


FIGURE 15. STORM MODEL SIMULATION OF STORAGE AND TREATMENT FOR WET-WEATHER QUALITY CONTROL

intermittently, annual operations and maintenance costs are greatly affected by the number of hours the facility is utilized. As a general rule, a facility will operate a greater amount of the time if it incorporates storage. An examination of Table 36 reveals that annual operation and maintenance costs are 16.7 percent of the total annual costs for the contact stabilization unit. In the case of the swirl concentrator, the percentage is 27.3. Annual operation and maintenance costs for other units fall in between these two values. Based on this analysis, it was decided to assume annual operation and maintenance costs as 20 percent of

the total annual costs for all treatment devices. Cost functions developed for various wet-weather quality control devices are presented in Table 37. These costs include provisions for sludge handling, engineering, contingencies, and land costs.

All treatment units exhibit economies of scale, i.e., unit cost decreases as plant size increases. Thus, there is an incentive to build larger units. The optimum size treatment unit can be found by comparing the savings in treatment cost of going to a larger unit with the increased piping costs. For example, if one is comparing building two 10 mgd (37,850 m^3/day) plants with building one 20 mgd (75,700 m^3/day) plant and a pipeline, the breakeven pipe length, L is found using

Two plants One plant + pipeline

$$s(10)^z + s(10)^z = s(20)^z + K(10)^y(L) \quad (58)$$

where: s, x, z, K and y = coefficients.

Unfortunately, data on the number and flow rates of storm water discharges in urban areas could not be found. Thus, it is not possible to determine the optimum mix of treatment plants and pipelines. Therefore, representative treatment costs were used as shown in Table 36. A 30 mgd plant size was selected since it represents a reasonable upper limit on the range of strong economies of scale. The average costs are based on a microstrainer for primary treatment and contact stabilization for secondary treatment.

Cost data on detention basins built in the Chicago area for temporary storage of runoff are listed in Table 38. Costs of storage tanks built for the purpose of wet-weather quantity and quality control as well as for dry-weather quantity control are also included in this table. Due to the wide variations in these figures, an attempt was made to verify these costs using excavation costs as the basis. Storage costs based on unit excavation costs are listed in Table 38. The unit cost of equalization and the estimated costs of rooftop and parking lot storage basins for sewage treatment plants are also shown in Table 38. Lastly, analysis of recent estimates of storage costs developed by Benjes et al indicate the following unamortized capital cost C ($ x 10^6) as a function of storage volume, S (million gallons) [58].

TABLE 37. ANNUAL COST FUNCTIONS FOR WET WEATHER CONTROL DEVICES [a,b,i]

Device	Control Alternative	Annual Cost: $/yr Amortized Capital CA = IT^m or IS^m		Operation and Maintenance OM = pT^q		Total TC = wT^z or wS^z	
		I	m	p	q	w	z
Primary	Swirl Concentrator[c,d,e]	1,971.0	0.70	584.0	0.70	2,555.0	0.70
	Microstrainer[e,f]	7,343.8	0.76	1,836.0	0.76	9,179.8	0.76
	Dissolved Air Flotation[e]	8,161.4	0.81	2,036.7	0.84	10,198.1	0.84
	Sedimentation[e]	32,634.7	0.70	8,157.8	0.70	40,792.5	0.70
	Representative Primary Device — Total Annual Cost = $4,000 per mgd ($1.06/m^3/day)						
Secondary	Contact Stabilization[g]	19,585.7	0.85	4,894.7	0.85	24,480.4	0.85
	Physical-Chemical[e]	32,634.7	0.85	8,157.8	0.85	40,792.5	0.85
	Representative Secondary Device Total Annual Cost = $15,000 per mgd ($3.93/m^3/day)						
Storage	High Density (15/ac)	51,000.0	1.00	---	--	51,000.0	1.00
	Low Density (5/ac)	10,200.0	1.00	---	--	10,200.0	1.00
	Parking Lot[h]	10,200.0	1.00	---	--	10,200.0	1.00
	Rooftop[h]	5,100.0	1.00	---	--	5,100.0	1.00
	Representative Annual Storage Cost[j] ($ per ac-in) = $122 $e^{0.16(PD_d)}$						

T = Wet-weather treatment rate in million gallons per day (mgd)

S = Storage volume in million gallons

one million gallons = 3,785 m^3

[a] ENR = 2,200. Includes land costs, chlorination, sludge handling, engineering and contingencies.

[b] Sludge handling costs based on data from Batelle Northwest [57]

[c] Field and Moffa [53]

[d] Benjes et al [58]

[e] Lager and Smith [46]

[f] Maher [55]

[g] Agnew et al [56]

[h] Wiswall and Robbins [59]

[i] For T $\leq$ 100 mgd (378,500 m^3/day).

[j] PD_d = developed population density, persons/acre.

TABLE 38. INITIAL CAPITAL COST OF STORAGE FACILITIES[a]

	Capacity		Capital Cost		
	mil gal	(1,000 m^3)	$/gal	($/liter)	
Storage Reservoirs[b]					
Hillside Park	11.4	(43.1)	0.01	(0.003)	Earthen Basin
Heritage Park	36.5	(138.0)	0.01	(0.003)	Earthen Basin
Oak Lawn	7.8	(29.5)	0.02	(0.005)	Earthen Basin
Middle Fork North Branch	195.5	(740.0)	0.02	(0.003)	Earthen Basin
Wilke-Kirchoff	32.6	(123.0)	0.03	(0.008)	Earthen Basin
Melvina Dutch	53.8	(204.0)	0.03	(0.008)	Earthen Basin
Oak Hill Park	25.1	(95.0)	0.02	(0.005)	Earthen Basin
Dolphine Park	53.8	(204.0)	0.01	(0.003)	Earthen Basin
Average	52.1	(197.0)	0.019	(0.005)	
Storage Tanks[e]					
Cottage Farm, Boston[c]	1.3	(4.9)	5.21[d]	(1.38)	Covered Conc. Tanks
Spring Creek, New York[c]	10.0	(37.8)	2.33	(0.62)	Covered Conc. Tanks
Chippewa Falls, Wisconsin[c]	2.8	(10.6)	0.29	(0.08)	Asphalt Paved Basin
Humboldt Avenue, Milwaukee[c]	4.0	(15.1)	0.55	(0.14)	Covered Conc. Tanks
Seattle, Washington	32.0	(121.0)	0.25	(0.07)	In-line
Whittier Narrow, Columbus[c]	4.0	(15.1)	1.70	(0.45)	Open Concrete Tanks
Average	9.0	(34.1)	1.72	(0.45)	
Based on Excavation Costs[f]					
$2/$yd^3$ ($2.62/$m^3$)			0.01	(0.003)	Earthen Basin
$5/$yd^3$ ($6.54/$m^3$)			0.025	(0.007)	Earthen Basin in Rock
Equalization Basins for Dry Weather Sewage Treatment Plants[g]	1.0	(3.8)	0.22	(0.06)	Earthen Basin
	3.0	(11.4)	0.10	(0.03)	Earthen Basin
	10.0	(37.8)	0.06	(0.02)	Earthen Basin
	1.0	(3.8)	0.39	(0.10)	Concrete Basin
	3.0	(11.4)	0.28	(0.07)	Concrete Basin
	10.0	(37.8)	0.25	(0.07)	Concrete Basin
Other[h]					
Parking Lots			0.10	(0.03)	
Rooftops			0.05	(0.02)	

[a]Based on ENR = 2,200

[b]Metropolitan Sanitary District of Greater Chicago

[c]Also used for storm water treatment

[d]Includes pumping station, chlorination and outfall facilities.

[e]Lager and Smith [46]

[f]Soil Conservation Service, Gainesville, FL.

[g]Flow Equalization - Plus for Wastewater Treatment Plants, Civil Eng., 9/75.

[h]Wiswall and Robbins [59]

Type	Equation	Unit Cost @ S = 10 mg $/gal ($/litre)
Earthen	$C = 0.025\ S^{0.73}$	$0.013 ($0.0034)
Concrete w/o Cover	$C = 0.350\ S^{0.58}$	$0.133 ($0.0350)
Concrete w Cover	$C = 0.400\ S^{0.79}$	$0.250 ($0.0660)

The data indicate wide variation in the costs of storage. Thus, the relatively simple relationship shown in Table 38 was used. Annual storage costs are estimated as a function of gross population density. At low population densities, land values are relatively low. Thus land-intensive storage facilities, e.g., shallow ponds, can be used. At higher population densities, land values increase to the point where storage tanks become more economical. The data presented in Table 38 are based on differing assumptions regarding land values. In some cases the land is free (part of an easement) whereas in others it is valued highly. Thus, a simplified approximation was used. The curve was derived using an unamortized capital cost of $0.10 per gallon ($0.026 per litre) for PD_d = 5 persons per acre (12.4 per ha) and $0.50 per gallon ($0.132 per litre) for PD = 15 persons per acre (37.1 per ha).

5.3 Relationship between Storage/Treatment and Percent Pollution Control

5.3.1 Use of STORM

STORM was used to evaluate various storage/treatment options for controlling storm water runoff pollution. This model assumes that the study area can be characterized as a single catchment from which hourly runoff is directed to storage and treatment.

STORM uses a simplified rainfall/runoff relationship, neglects the transport of water through the city and assumes a very simple relationship between storage and treatment. However, these simplifications are essential if one hopes to do a continuous simulation. The continuous simulation approach was used because no general concurrence exists regarding an appropriate single event that one should analyze.

The degree of control can be expressed in terms of the percent of the runoff treated, the annual number of overflows, or the amount of pollutants discharged to the receiving waters.

As described in the User's Manual, STORM computes the runoff based on the composite runoff coefficient and the effective precipitation [23]. The depression storage must be satisfied before the runoff coefficient is applied to the precipitation. The amount of depression storage available in ditches, depressions, and other surfaces is a function of the past precipitation and the evaporation rates. Each hour that runoff occurs, the model compares it to the treatment rate. As long as the runoff rate is less than or equal to the treatment rate, all the runoff passes directly through the treatment plant and storage is not utilized. When the runoff rate exceeds the treatment rate, the excess runoff is sent to storage. If excess runoff occurs frequently enough to exceed the storage capacity then overflow occurs. When runoff falls below the treatment rate then storage is depleted at the excess treatment rate. The hourly occurrence of treated runoff, stored runoff, and runoff that has overflowed is tabulated for the entire record of rainfall. Included in the output is the annual number of overflow events and the percentage of the runoff that overflowed to the receiving waters. This type of analysis was carried out for different storage capacities and treatment rates.

5.3.2 STORM input data

STORM requires several input parameters that characterize the urban area under study. These include hourly precipitation, total area, land use types and percentages, percent imperviousness, and curb length per area for each land use [23]. In order to apply STORM, these data were collected or derived for nine urban areas within the Ontario portion of the Great Lakes Basin. The local data were collected by on-site interviews.

Precipitation data were acquired from the Department of the Environment. The records were of varying length, from a few years to several decades. Additionally, the records were supplied in two parts. One part included only rainfall and was usually restricted to the months

from April to October. This portion was previously formatted on magnetic tape, which facilitated a frequency analysis of this restricted rainfall record. This allowed the selection of one year (limited) of rainfall to characterize the entire record of each city. After the year was selected, the accompanying months of precipitation (primarily snowfall) were taken from written records and added to the restricted rainfall record. The precipitation for the selected year for each city was totalled and compared to the mean annual average. These values are shown in Figure 16. In some cases, it was apparent that although the rainfall frequency for the selected year was typical, the snowfall was not. Therefore, four of the nine cities, Burlington, St. Catharines, Kingston, and Sault Ste. Marie, were chosen to make the final STORM runs. It should be noted that precipitation patterns over Ontario show two distinct trends. In Figure 17, it can be seen that below 44^{o}N, the monthly precipitation is very stable. Above 44^{o}N the trend is toward a peak in the summer months. Therefore the selection of the four cities to represent the entire region seemed adequate. Sault Ste. Marie provides a good representation of the northern section of Ontario, while the three other cities adequately represent the southern section of the study area.

Snowfall is a significant component of Ontario's precipitation total, ranging from a low of 4.0 inches (10.2 cm) water equivalent near Windsor, to a high of 14.0 inches (36 cm) north of Sault Ste. Marie. STORM uses the degree-day for the computation of snowmelt with the option of applying this formulation or simply ignoring snowmelt and allowing snow to act as rainfall. A runoff frequency analysis was performed on the cities of Thunder Bay and Windsor to determine the effect of this routine. Runs were made with and without the method shown above. The results are shown in Figures 18 and 19. The figures show a difference in frequency; therefore, the snowmelt routine in STORM was used in the final STORM run.

Daily evaporation rates for each month were estimated from a report by Phillips and McCulloch [60]. These were available for only a few stations in Ontario and the evaporation rates for the four test cities were assigned on the basis of proximity to these stations. The depression storage is assumed to be 0.01 inches for all cities. The input data used to run STORM for the developed areas of the four selected test cities is summarized in Table 39.

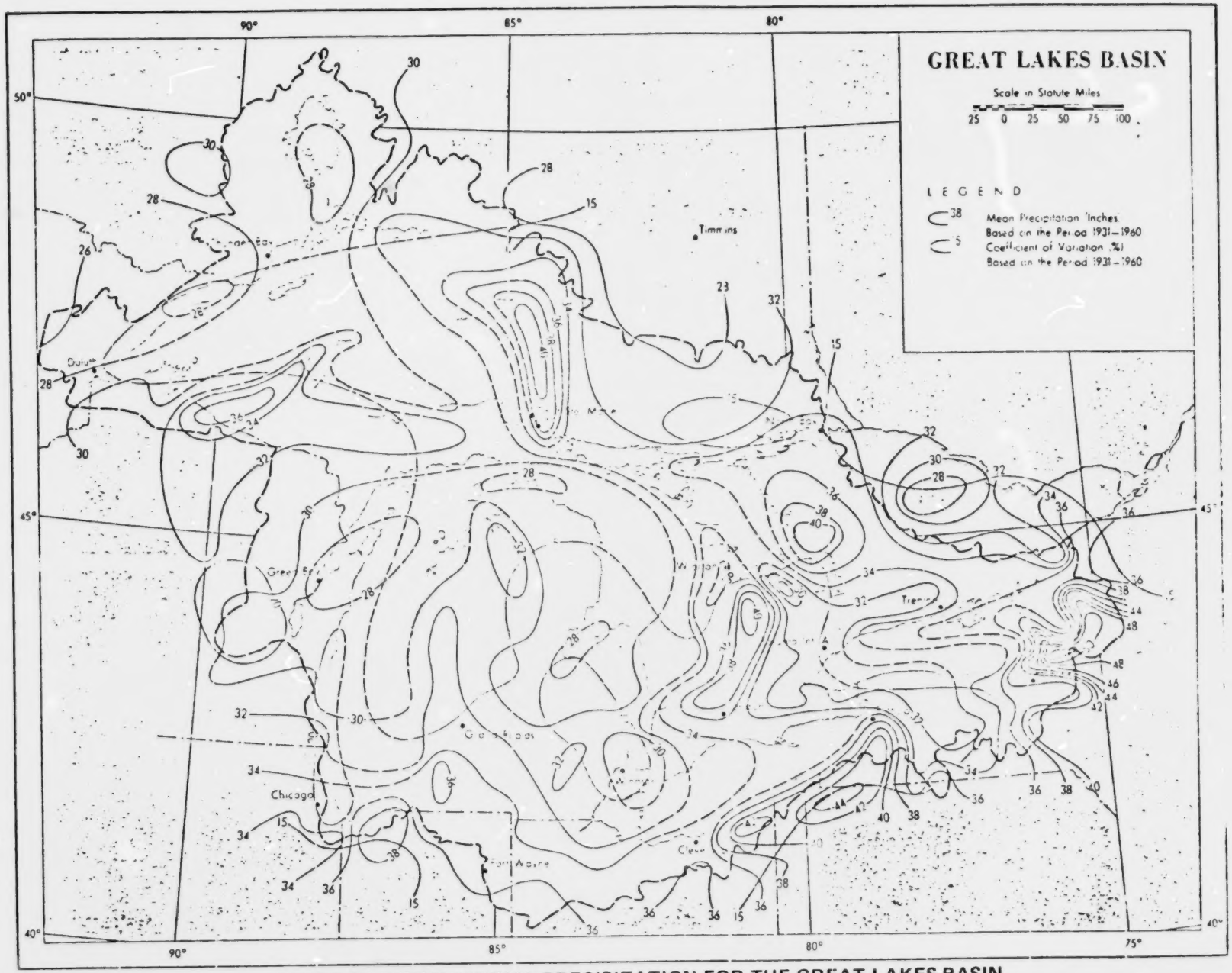


FIGURE 16. MEAN ANNUAL PRECIPITATION FOR THE GREAT LAKES BASIN.
(After Phillips and McCulloch,[60] Chart 21.)

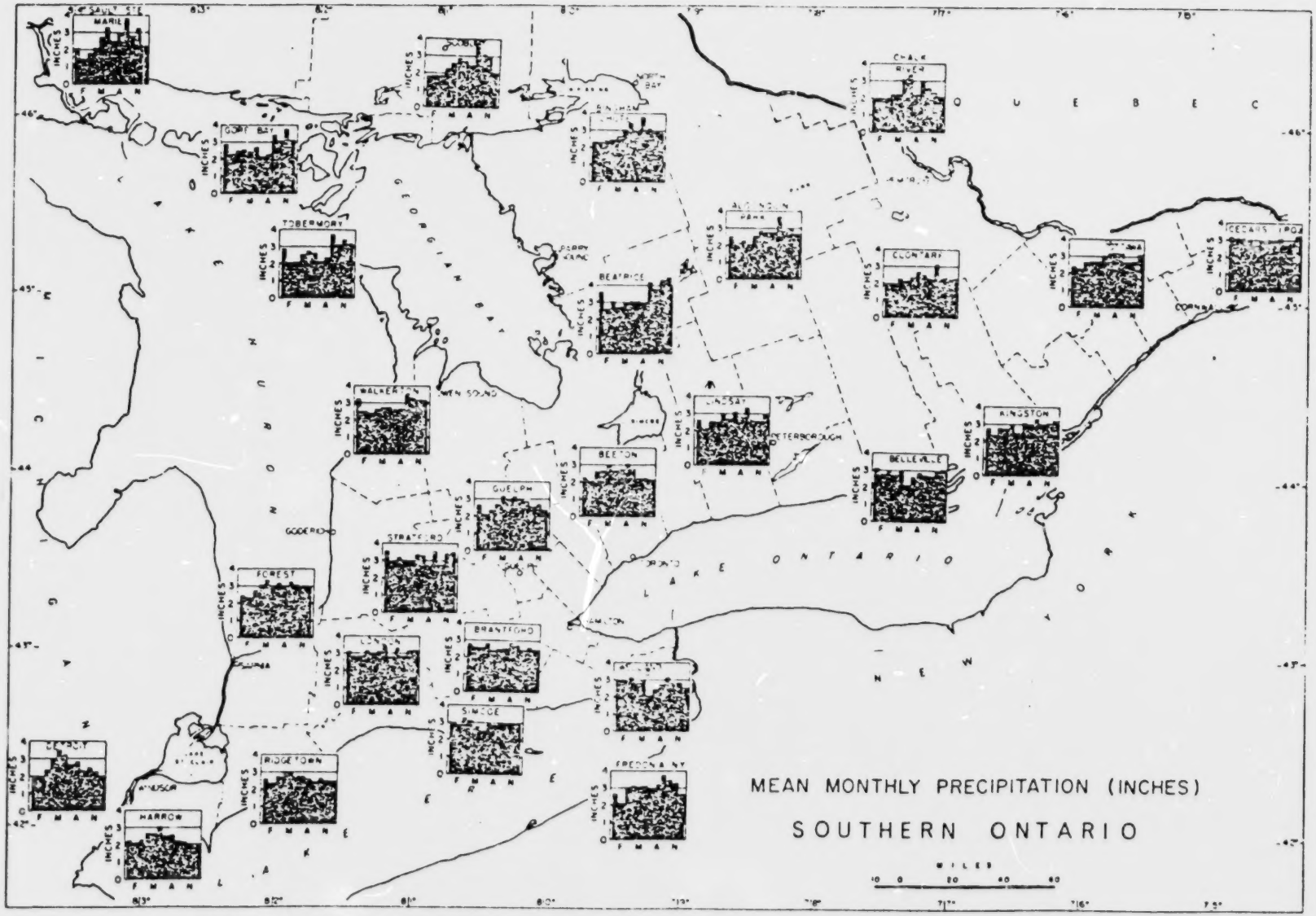


FIGURE 17. MEAN MONTHLY PRECIPITATION (After Brown, McKay and Chapman,[61] p. 35)

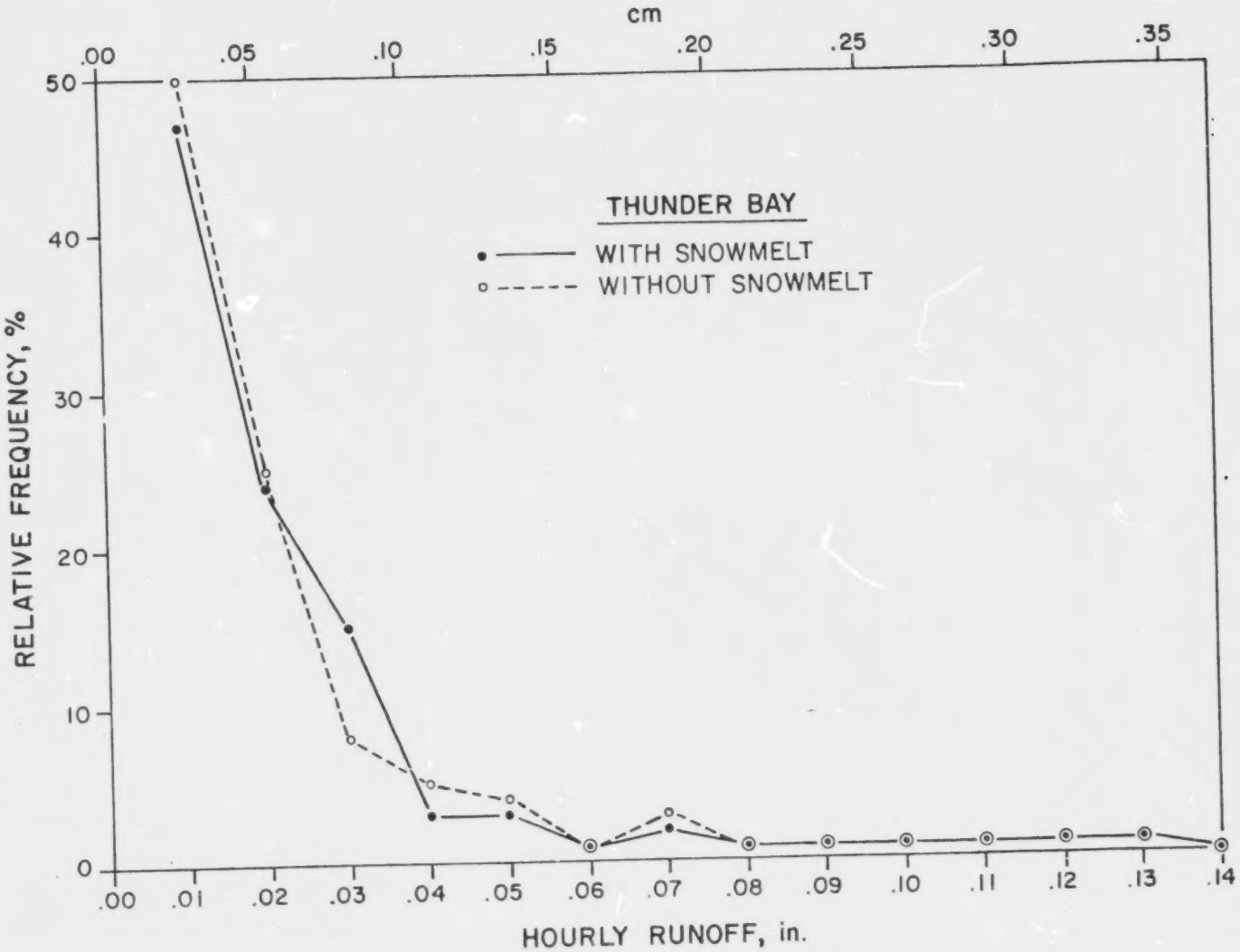


FIGURE 18. RUNOFF FREQUENCY, THUNDER BAY, 1971.

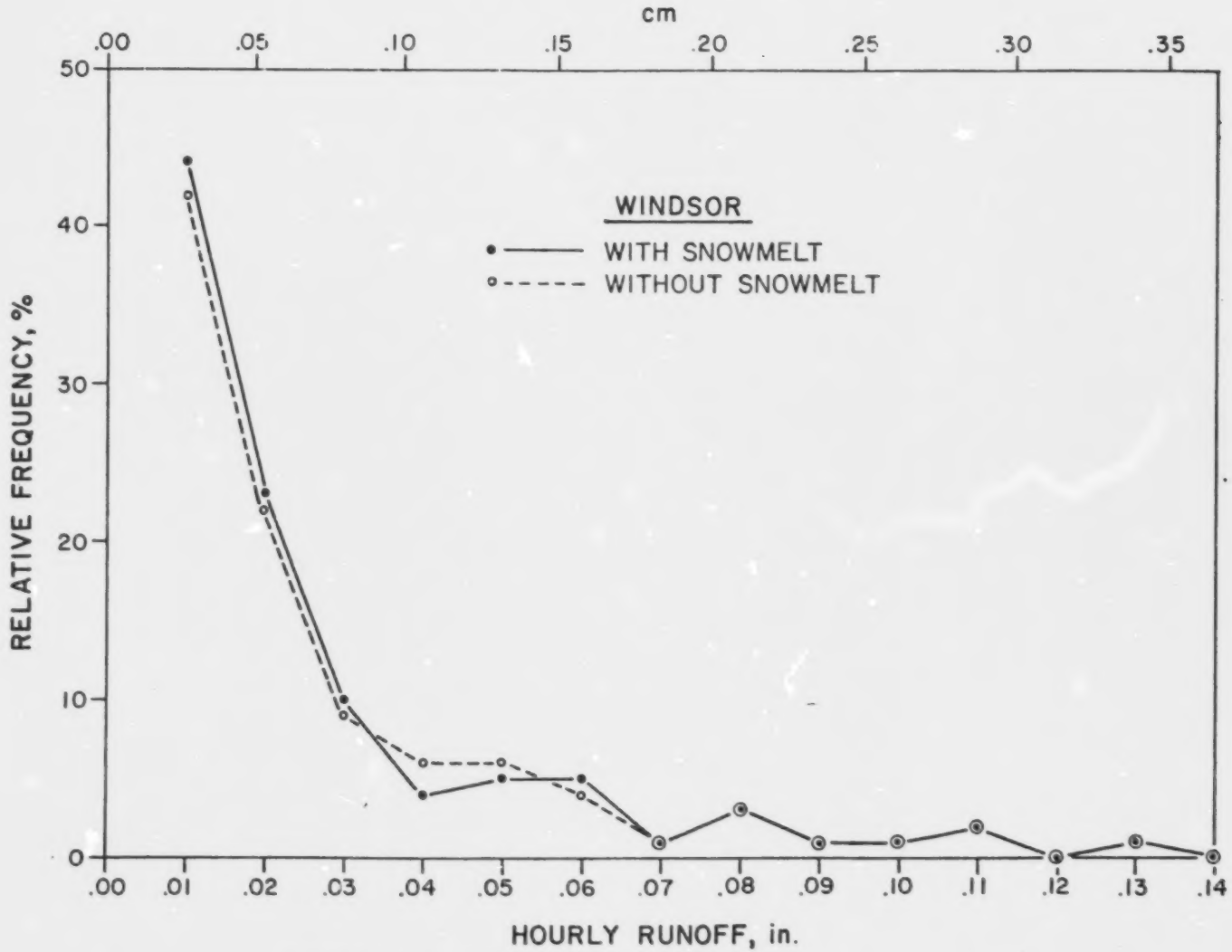


FIGURE 19. RUNOFF FREQUENCY, WINDSOR, 1973.

TABLE 39. STORM INPUT DATA FOR TEST CITIES

Study Area:	Burlington
Developed Area:	8687 ac (3516 ha)
Test Year:	1973
Precipitation:	32.38 in. (82.25 cm)

Daily evaporation rates for each month, Jan-Dec, in/day (cm/day)

0.00	0.00	0.05	0.05	0.13	0.15	0.17	0.14	0.10	0.06	0.05	0.00
(0.00)	(0.00)	(0.13)	(0.13)	(0.33)	(0.38)	(0.43)	(0.36)	(0.25)	(0.15)	(0.13)	(0.00)

Study Area:	Kingston
Developed Area:	4706 ac (1905 ha)
Test Year:	1965
Precipitation:	37.81 in. (96.04 cm)

Daily evaporation rates for each month, Jan-Dec, in/day (cm/day)

0.00	0.00	0.05	0.05	0.13	0.15	0.17	0.14	0.10	0.06	0.05	0.00
(0.00)	(0.00)	(0.13)	(0.13)	(0.33)	(0.38)	(0.43)	(0.36)	(0.25)	(0.15)	(0.13)	(0.00)

Study Area:	St. Catharines
Developed Area:	10976 ac (4442 ha)
Test Year:	1973
Precipitation:	32.37 in. (82.22 cm)

Daily evaporation rates for each month, Jan-Dec, in/day (cm/day)

0.00	0.00	0.05	0.05	0.13	0.15	0.17	0.14	0.10	0.06	0.05	0.00
(0.00)	(0.00)	(0.13)	(0.13)	(0.33)	(0.38)	(0.43)	(0.36)	(0.25)	(0.15)	(0.13)	(0.00)

Study Area:	Sault Ste. Marie
Developed Area:	8516 ac (3446 ha)
Test Year:	1969
Precipitation:	36.69 in. (93.19 cm)

Daily evaporation rates for each month, Jan-Dec, in/day (cm/day)

0.00	0.00	0.04	0.04	0.09	0.11	0.12	0.10	0.06	0.04	0.04	0.00
(0.00)	(0.00)	(0.10)	(0.10)	(0.23)	(0.28)	(0.30)	(0.25)	(0.15)	(0.10)	(0.10)	(0.00)

Burlington, Kingston, St. Catharines - estimated from Guelph "pan" evaporation: land evaporation = 0.70 "pan" evaporation.

Sault Ste. Marie - estimated from Seney, Michigan "pan" evaporation: land evaporation = 0.70 "pan" evaporation.

5.4 Results

For each storage/treatment rate combination there is a value for the percent of the runoff and pollutants which are "treated". Preliminary analysis of STORM runs made for the U.S. assessment indicated little year to year variation in results. Thus, only one year of precipitation was used to derive the isoquant curves. By making several runs at different combinations of treatment and storage, points were generated representing different levels of control. Then isoquants were drawn connecting the points that represent combinations of storage capacities and treatment rates which give equivalent percent runoff and/or pollutant "treated". If the concentration of pollutants is constant and "treatment" efficiency, η, is 1.0, then percent runoff control is synonymous with percent pollutant control. Obviously, this is not the case. Thus, account needs to be taken of:

1) treatment efficiency, and
2) variable concentration due to first flush effects.

5.4.1 Adjustment for treatment efficiency

Let R denote the percent runoff control and equal treatment plant efficiency. If R_1 denotes the percent pollutant control, then to realize R_1, one needs to process R_1/η of the runoff. Note that R_1 may be percent BOD removal, percent SS removal, etc. In Table 39, representative treatment efficiencies, in terms of BOD_5 removal, were derived for primary and secondary devices. These values are as follows:

Treatment Device	Assumed Efficiency, η (BOD_5 Removal)
Primary	0.40
Secondary	0.85

Thus, if one desires 25 percent BOD_5 removal with a primary device, then 62.5 percent of the runoff volume must be processed, whereas only 29.4 percent of the runoff needs to be processed if a secondary device is selected. Thus, to convert percent runoff control isoquants to percent pollutant control isoquants, one uses:

$$R = R_1/\eta \tag{59}$$

5.4.2 Adjustment for first flush

STORM estimates the percent pollutant control as well as percent runoff control. The STORM model runs incorporated the standard first flush assumption which is used in the model, i.e., that the amount of pollutant removal at any time, t, is proportional to the amount remaining and that a uniform rainfall of one-half inch per hour would wash away 90 percent of the pollutant in one hour. If a first flush is assumed, then storage and treatment can be operated more effectively because of the greater relative importance of capturing the initial runoff. The first flush is accounted for by defining the output in terms of pollutant control directly.

5.4.3 Mathematical representation of isoquants

The storage/treatment isoquants are of the form:

$$T = T_1 + (T_2 - T_1)e^{-KS} \tag{60}$$

where: T = wet-weather treatment rate, inches per hour,
T_1 = treatment rate at which isoquant becomes asymptotic to the ordinate, inches per hour,
T_2 = treatment rate at which isoquant intersects the abscissa, inches per hour,
S = storage volume, inches, and
K = constant, $inch^{-1}$.

A relatively large storage reservoir is required to operate the treatment unit continuously. Thus, first flush effects would be dampened out and the effluent concentration from the reservoir should be relatively uniform. Thus, if storm water entering the treatment plant was a relatively uniform concentration, then T_1 can be found as follows:

$$T_1 = \frac{AR}{8,760}\left(\frac{R}{100}\right) = aR \tag{61}$$

where: a = coefficient,
AR = annual runoff, inches per year, and
R = percent runoff control.

By relating the parameters T_1, $T_2 - T_1$ and K to the level of control R, one equation was developed for each of the four cities. The $T_2 - T_1$ and K terms versus R were found to be of the following general form:

$$T_2 - T_1 = be^{cR} \quad (62)$$

$$K = de^{-fR} \quad (63)$$

Based on this analysis the following general equation for the isoquants is obtained:

$$T = aR + be^{cR-(de^{-fR})S} \quad (64)$$

The values of parameters a, b, c, d, and f for various cities are presented in Table 40, for percent pollutant control. The correlation coefficients for the equations for the four cities are also shown in this table. In general, the fit is excellent.

The results for the four cities are shown in Figures 20, 21, 22 and 23. Each figure shows the isoquants calculated by the isoquant equation. Also shown are some actual data points for a treatment rate of 0.01 inches per hour and varying amounts of storage.

TABLE 40. VALUES OF PARAMETERS AND CORRELATION COEFFICIENTS FOR ISOQUANT FACTORS

Percent BOD Control with First Flush, $\eta = 1.0$

Test City	a in $hr^{-1}(\%\ R)^{-1}$ ($cm\ hr^{-1}$)	b in hr^{-1} ($cm\ hr^{-1}$)	c $(\%\ R)^{-1}$	d in^{-1} (cm^{-1})	f $(\%\ R)^{-1}$	Correlation Coefficients $T_2-T_1=be^{cR}$	$K=de^{-fR}$
Burlington	0.0000121 (0.0000310)	0.0017093 (0.0043400)	0.0414918	210.4827 (82.8000)	0.0298024	0.994	-0.988
Kingston	0.0000127 (0.0000320)	0.0013611 (0.0034600)	0.0384055	241.9431 (95.3000)	0.0306992	0.995	-0.992
St. Catharines	0.0000130 (0.0000330)	0.0016126 (0.0041000)	0.0434050	240.4267 (94.7000)	0.0298348	0.995	-0.983
Sault Ste. Marie	0.0000166 (0.0000421)	0.0018704 (0.0074900)	0.0449201	191.309 (75.300)	0.0334145	0.992	-0.994

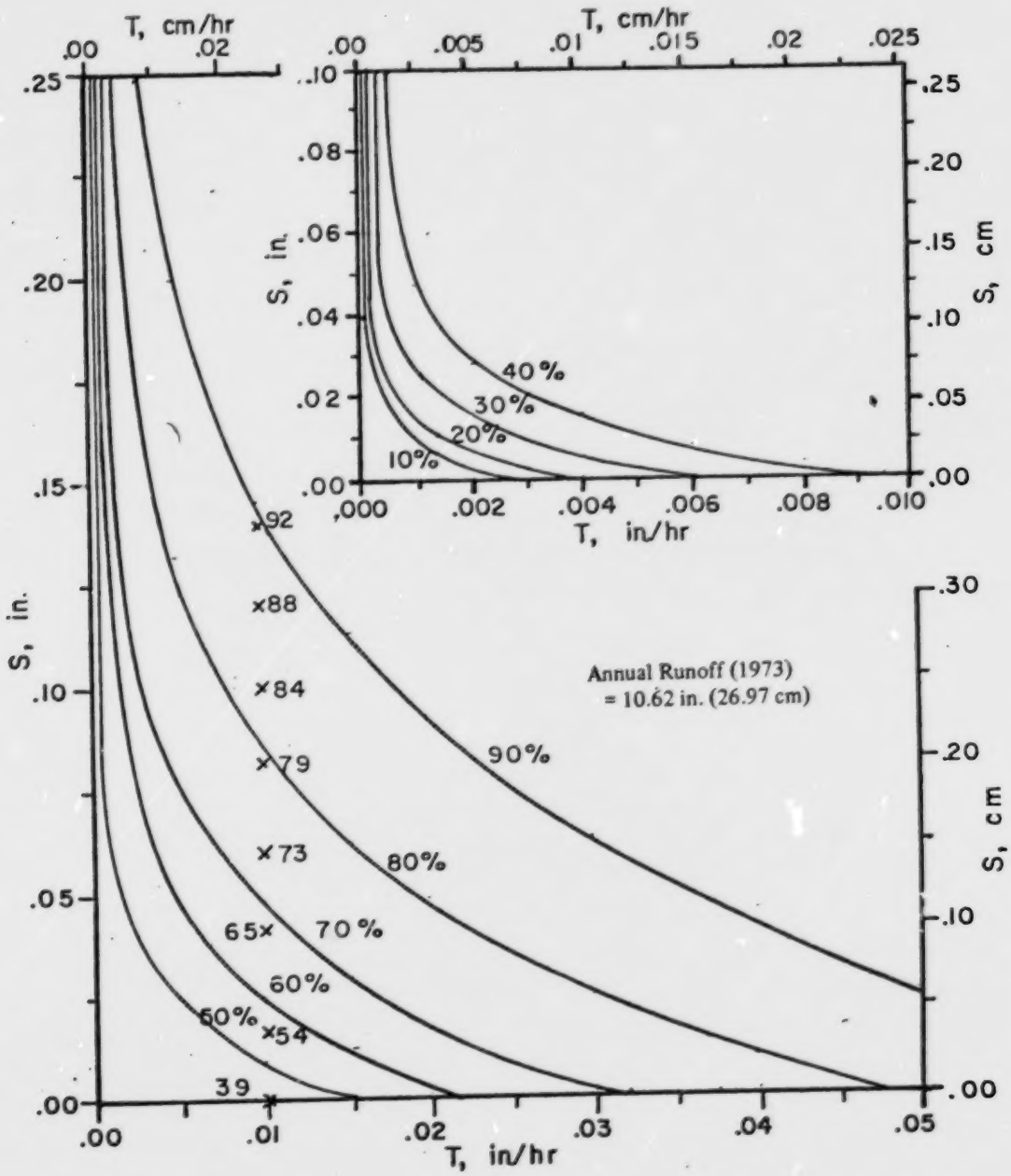


FIGURE 20. STORAGE-TREATMENT ISOQUANTS FOR PERCENT BOD REMOVAL WITH FIRST FLUSH FOR BURLINGTON

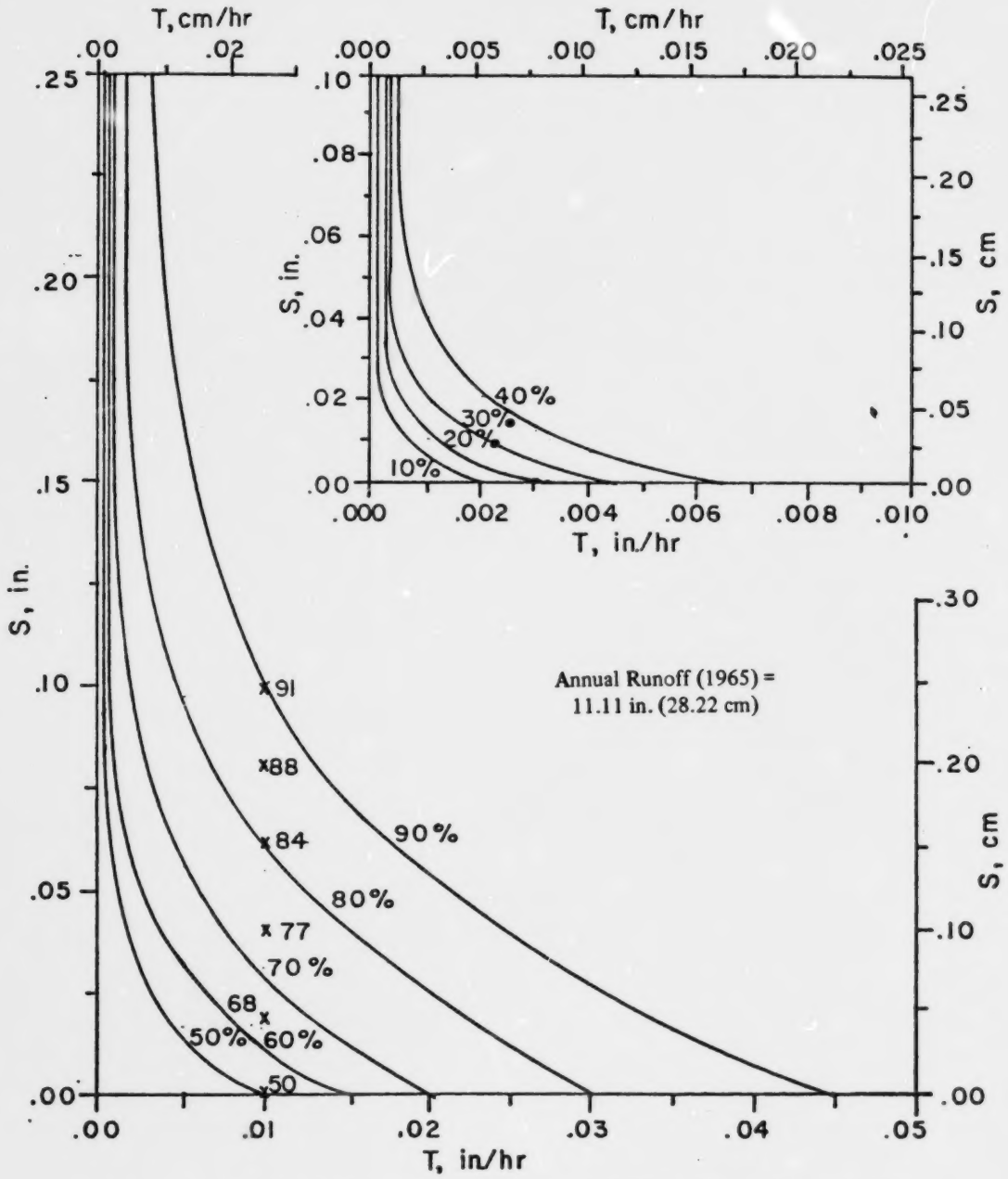


FIGURE 21. STORAGE-TREATMENT ISOQUANTS FOR PERCENT BOD REMOVAL WITH FIRST FLUSH FOR KINGSTON

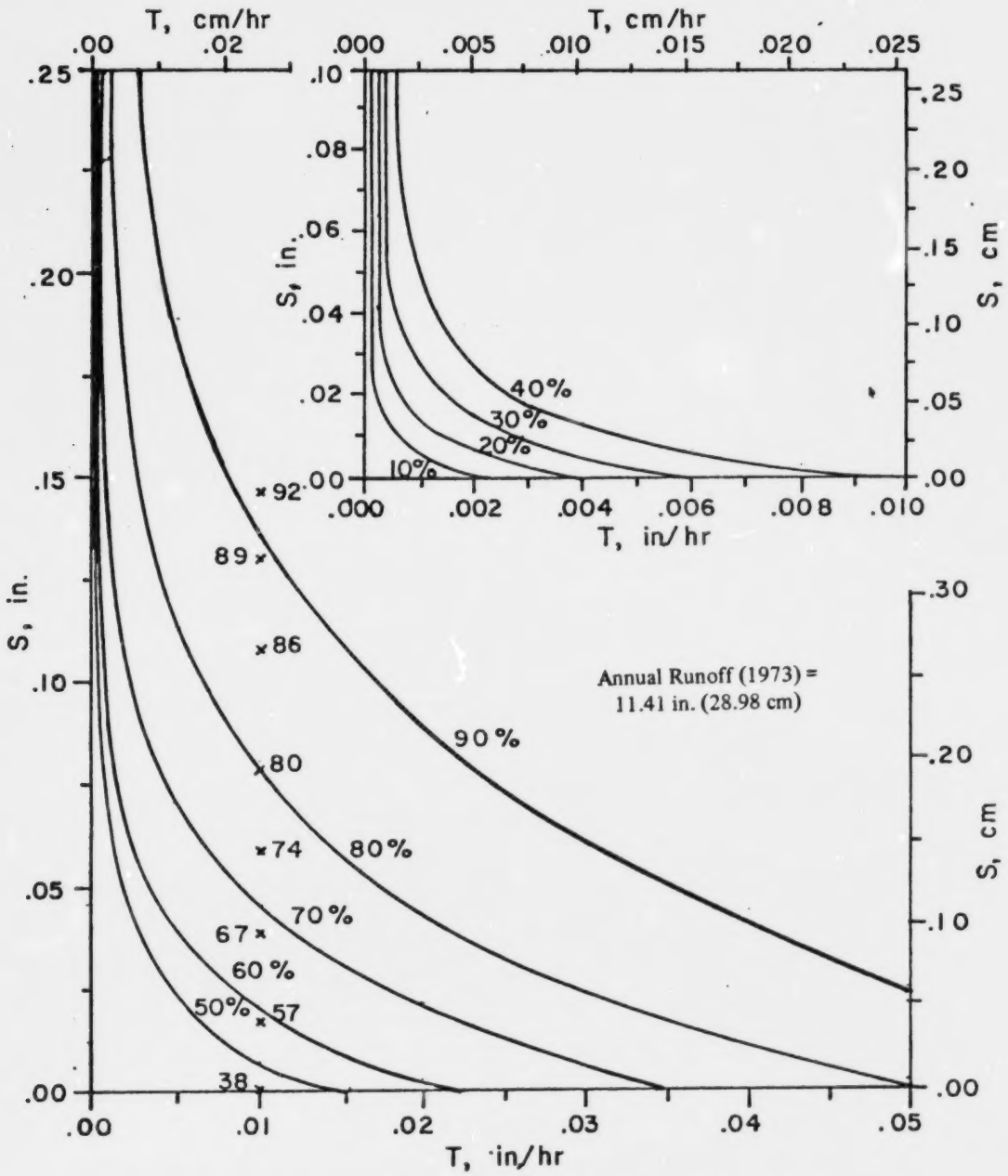


FIGURE 22. STORAGE-TREATMENT ISOQUANTS FOR PERCENT BOD REMOVAL WITH FIRST FLUSH FOR ST. CATHARINES

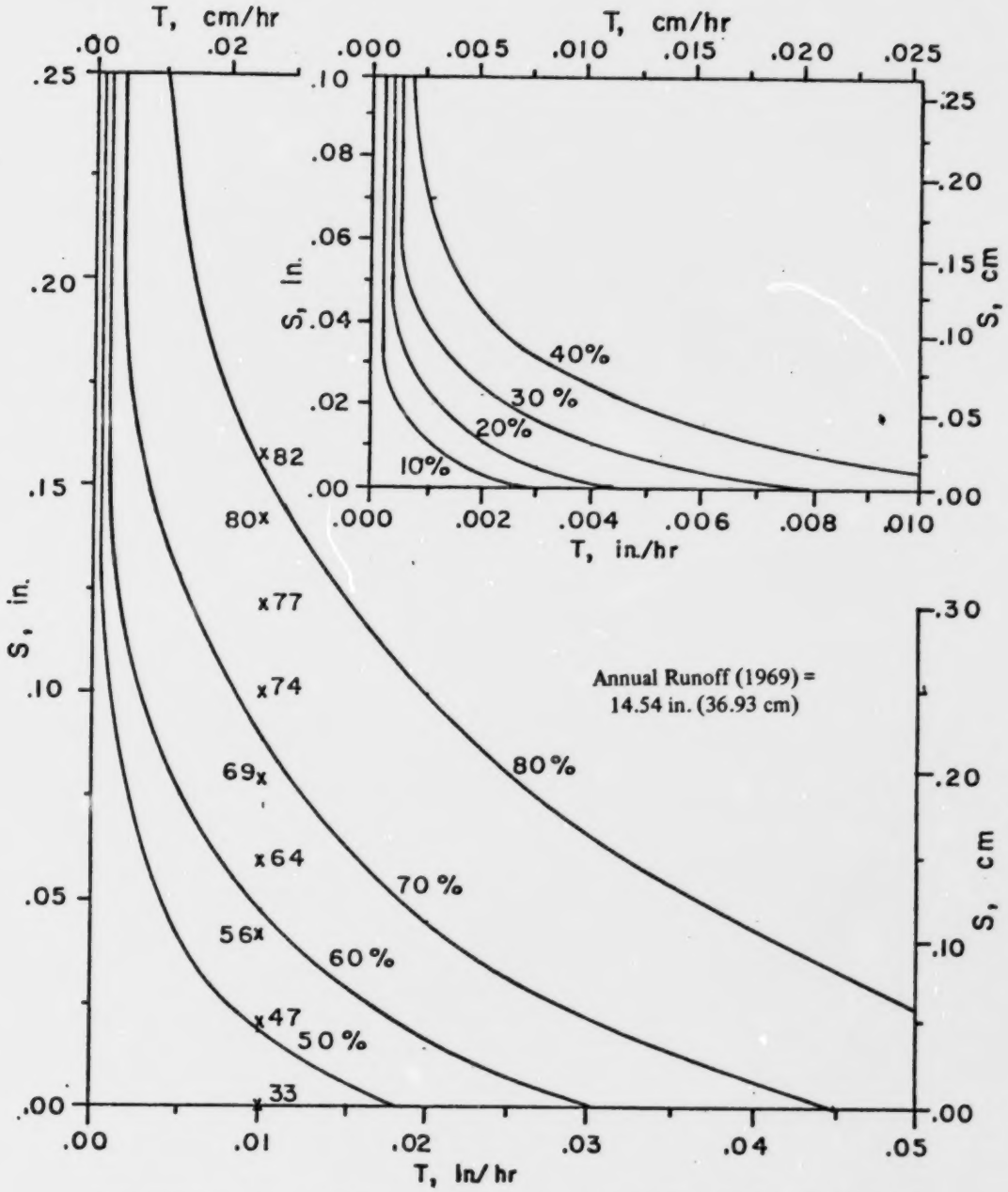


FIGURE 23. STORAGE-TREATMENT ISOQUANTS FOR PERCENT BOD REMOVAL WITH FIRST FLUSH FOR SAULT STE. MARIE

The optimum expansion path can be found using

$$\frac{c_T}{c_S} = MRS_{ST} \tag{65}$$

where: c_S = unit cost of storage,
c_T = unit cost of treatment, and
MRS_{ST} = marginal rate of substitution of storage for treatment.

The value of c_S and c_T are presented in Table 34.

Analysis of the figures indicates that if $c_T/c_S \leq 25$, then treatment alone should be used. From Table 34:

$$\frac{c_T}{c_S} = \frac{c_T}{122e^{0.16(PD)}}$$

For primary treatment, $c_T = \$2{,}610/\frac{\text{acre-inch}}{\text{hour}}$.

Thus, even at zero population density, $c_T/c_S = 21.4$ so that the optimum policy is to use treatment only.

So that,

for secondary treatment, letting $c_T/c_S = 25$, and knowing that

$c_T = \$9{,}800/\frac{\text{acre-inch}}{\text{hour}}$, yields

$$122e^{0.16(PD)} = \frac{9800}{25}, \text{ or}$$

$PD_d = 7.29$ persons per acre.

If PD_d is higher than about 7.5, then the relative cost of storage is such that it is again optimal to use treatment only. Using 7.5 persons per acre as the cutoff, then 12 of the 56 cities would use treatment only for the secondary control level. The remaining 44 cities would select a mix of storage and treatment.

It is simple to find the optimum expansion path graphically for the four test cities. Unfortunately, these results need to be extrapolated to all urbanized areas. It appeared that an analytical approach would provide a more general and consistent procedure. Thus, the isoquant

parameters were adjusted based on the runoff in the city under consideration relative to the reference city, i.e., let

AR_i = annual runoff in city i; i = 1,2, ..., 56

AR_j = annual runoff for test year in test city for region j (see Figures 20-23); j = 7,17,38,41.

Then, the isoquant coefficients are

$$a_{i,j} = AR_i/(8.76 \times 10^5) \tag{66}$$

$$b_{i,j} = \frac{AR_i}{AR_j} b_j, \tag{67}$$

$$c_{i,j} = c_j, \tag{68}$$

$$d_{i,j} = \frac{AR_j}{AR_i} d_j, \text{ and} \tag{69}$$

$$f_{i,j} = f_j \tag{70}$$

where $a_{i,j}$, $b_{i,j}$, $c_{i,j}$, $d_{i,j}$, and $f_{i,j}$ are parameters for city i in region j; and b_j, c_j, and f_j are the parameters for the test city in region j. The test cities are denoted as follows:

j=	City
7	Burlington
17	Kingston
38	St. Catharines
41	Sault Ste. Marie

5.4.4 Wet-weather quality control optimization

The wet-weather optimization problem, assuming linear costs, may be stated as follows:

minimize

$$Z = c_S S + c_T T \tag{71}$$

subject to

$$T = T_1 + (T_2 - T_1)e^{-KS}$$
$$T, S \geq 0$$

Solving this constrained optimization problem yields:

$$S^* = \max\left[\frac{1}{K} \ln \frac{c_T}{c_S}[K(T_2 - T_1)], 0\right] \quad (72)$$

where: S^* = optimal amount of storage, inches,

and $$T^* = T_1 + (T_2 - T_1)e^{-KS^*} \quad (73)$$

where: T^* = optimal amount of treatment, inches per hour.

Note that T^* is expressed as a function of S^*, so it is necessary to find S^* first. Knowing S^* and T^*, the optimal solution is:

$$Z^* = c_s S + c_T T^* \quad (74)$$

where: Z^* = total annual cost for optimal solution, dollars per acre.

Data needed to estimate T_1, T_2 and K have already been presented in the previous section.

For a primary device,

$$c_T = \$4{,}000/\text{mgd} = \$2{,}610/\frac{\text{acre-in}}{\text{hr}} \ (\$1.05/\text{m}^3/\text{day})$$

and $\eta = 0.40$.

For a secondary device,

$$c_T = \$15{,}000/\text{mgd} = \$9{,}800/\frac{\text{acre-in}}{\text{hr}} \ (\$2.32/\text{m}^3/\text{day}).$$

For storage cost,

$$c_s \ (\$/\text{acre-in.}) = 122\ e^{0.16(PD)} \quad (75)$$

where: PD = gross population density in persons per acre.

The above optimization procedure was programmed to generate curves, e.g., Figure 24, showing percent pollutant removed versus total annual costs for primary and secondary treatment in conjunction with storage. Note that for wet-weather control, marginal costs are increasing because of the disproportionately larger sized control units needed to capture the less frequent larger runoff volumes.

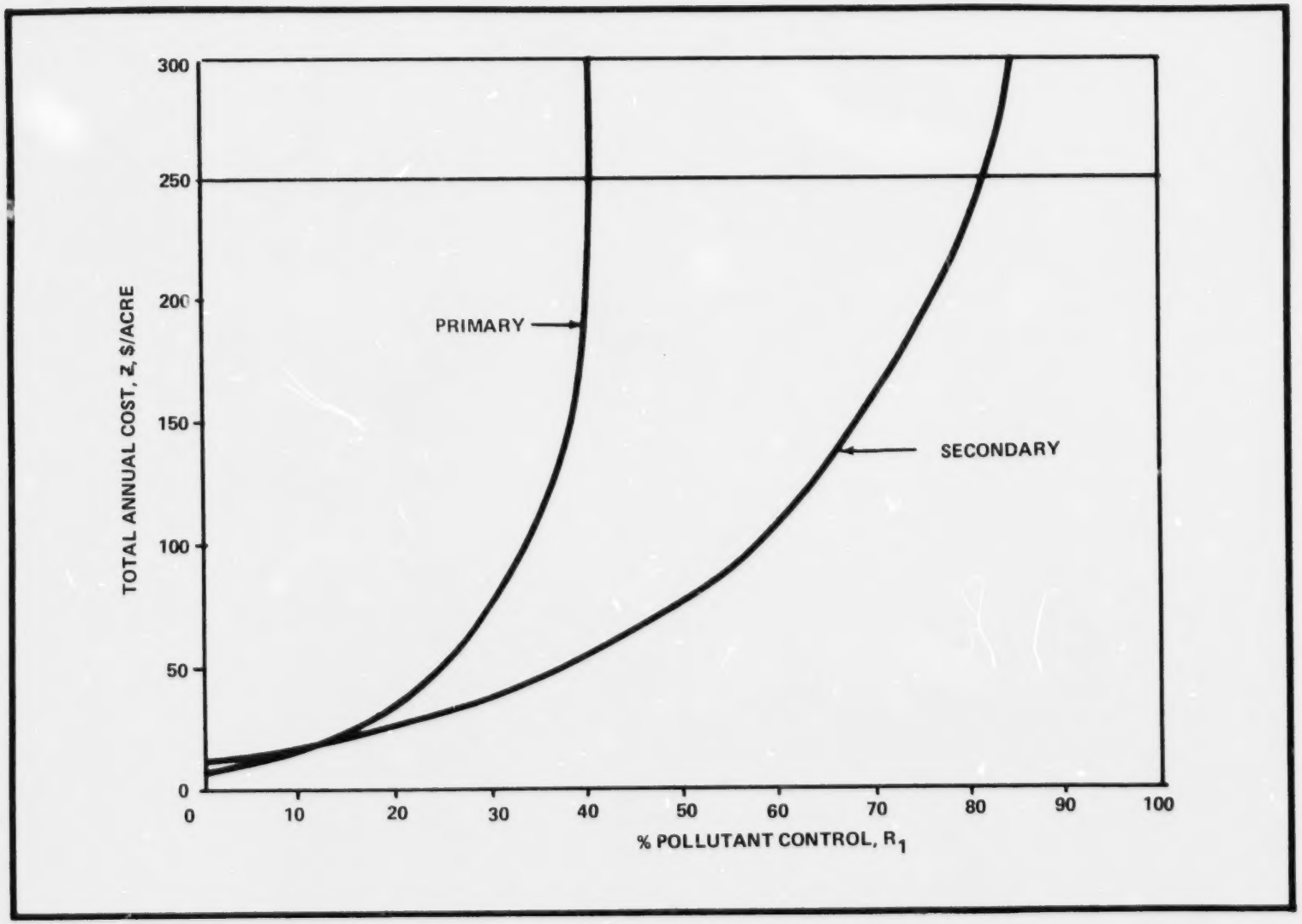


FIGURE 24. CONTROL COSTS FOR PRIMARY AND SECONDARY UNITS IN STORM SEWERED AREAS IN BURLINGTON

These results also permit one to decide whether a primary or a secondary level is more cost-effective in controlling smaller percentages of pollution. As seen in Figure 24, a primary control device is less expensive for low removals (say $\leq$ 20 percent), but it loses effectiveness at higher levels because of the disproportionately large storage requirements. Costs will be reported for 25, 50, and 75 percent control levels. Thus, the secondary cost curve can be used in this range. The primary curve will not be discussed further.

The curves shown in Figure 24 can be approximated by functions of the form:

$$Z = ke^{\beta R_1} \tag{76}$$

where: Z = total annual cost, dollars per acre,

k β = parameters,

R_1 = percent pollutant removal, $0 \leq R_1 \leq \overline{R}_1$, and

$\overline{R}_1$ = maximum percent pollutant removal.

The resulting costs for 25, 50, and 75 percent pollutant control for combined, storm, and unsewered areas are shown in Tables 41, 42 and 43, respectively. Note that the reference city and values of the cost equation parameters are also shown.

5.4.5 Estimating number of overflow events

Some urban areas have used the number of overflow events per year as an indication of level of control due to different storage/treatment combinations. The objective in this case would be to find the most economical combination of storage and treatment which would not allow the annual number of overflows to exceed a predetermined value. It would not seem logical to increase the treatment rate or storage capacity if the number of overflows did not decrease.

The number of overflow events is affected by the definition of an "event" used in the STORM model wherein an event is defined as starting when storage is utilized and ending when storage is depleted. Even though overflow may take place in two separate time frames, the two occurrences are considered to be parts of the same event if storage is utilized throughout the time frame.

TABLE 41. ANNUAL CONTROL COSTS - COMBINED AREAS

NO	URBANIZED AREA	REF CTY	EQN. (76) COEFS. k	EQN. (76) COEFS. β	CONTROL COST ($/ACRE) 25%	50%	75%
1	AJAX	7	30.34	.0485	101.	339.	1132.
2	AURORA	7	0.0	.0	0.	0.	0.
3	BARRIE	7	0.0	.0	0.	0.	0.
4	BELLEVILLE	17	22.82	.0435	68.	201.	597.
5	BRAMPTON	7	0.0	.0	0.	0.	0.
6	BRANTFORD	38	0.0	.0	0.	0.	0.
7	BURLINGTON	7	0.0	.0	0.	0.	0.
8	CHATHAM	38	13.88	.0398	38.	102.	275.
9	CHINGUACOUSY	7	0.0	.0	0.	0.	0.
10	COBOURG	17	0.0	.0	0.	0.	0.
11	DUNDAS	7	0.0	.0	0.	0.	0.
12	ETOBICOKE	7	0.0	.0	0.	0.	0.
13	GALT	7	0.0	.0	0.	0.	0.
14	GEORGETOWN	7	0.0	.0	0.	0.	0.
15	GUELPH	7	0.0	.0	0.	0.	0.
16	HAMILTON	7	16.97	.0394	45.	122.	326.
17	KINGSTON	17	23.52	.0432	69.	204.	599.
18	KITCH.-WATERLOO	7	0.0	.0	0.	0.	0.
19	LEAMINGTON	38	25.43	.0504	90.	316.	1116.
20	LINDSAY	17	0.0	.0	0.	0.	0.
21	LONDON	38	29.93	.0504	105.	371.	1307.
22	MARKAM	7	18.76	.0399	51.	138.	374.
23	MIDLAND	7	20.07	.0394	54.	144.	385.
24	MISSISSAUGA	7	0.0	.0	0.	0.	0.
25	NEWMARKET	7	0.0	.0	0.	0.	0.
26	NIAGRA FALLS	38	12.00	.0390	32.	85.	224.
27	NORTH BAY	41	26.75	.0521	98.	362.	1334.
28	OAKVILLE	7	0.0	.0	0.	0.	0.
29	ORILLIA	7	0.0	.0	0.	0.	0.
30	OSHAWA	7	0.0	.0	0.	0.	0.
31	OWEN SOUND	7	28.87	.0420	82.	236.	673.
32	PETERBOROUGH	17	0.0	.0	0.	0.	0.
33	PICKERING	7	0.0	.0	0.	0.	0.
34	PORT COLBOURNE	38	0.0	.0	0.	0.	0.
35	PORT ERIE	38	29.73	.0504	105.	370.	1304.
36	PRESTON	7	0.0	.0	0.	0.	0.
37	RICHMOND HILL	7	0.0	.0	0.	0.	0.
38	ST. CATHARINES	38	12.85	.0394	34.	92.	246.
39	ST. THOMAS	38	26.83	.0432	79.	233.	685.
40	SARINA	38	27.40	.0503	96.	339.	1193.
41	SLT. STE. MARIE	41	0.0	.0	0.	0.	0.
42	SCARBOROUGH	7	28.37	.0483	95.	317.	1058.
43	SIMCOE	38	29.09	.0504	103.	362.	1276.
44	STRATFORD	7	0.0	.0	0.	0.	0.
45	SUDBURY	41	0.0	.0	0.	0.	0.
46	THUNDER BAY	41	20.00	.0476	66.	217.	713.
47	TORONTO	7	30.16	.0483	101.	337.	1125.
48	TRENTON	17	0.0	.0	0.	0.	0.
49	WALLACEBURG	38	24.05	.0493	82.	282.	968.
50	WELLAND	38	27.56	.0482	92.	306.	1021.
51	WHITBY	7	0.0	.0	0.	0.	0.
52	WINDSOR	38	24.16	.0486	81.	274.	923.
53	WOODSTOCK	38	0.0	.0	0.	0.	0.
54	YORK	7	28.28	.0483	94.	316.	1055.
55	YORK, EAST	7	27.79	.0482	93.	310.	1035.
56	YORK, NORTH	7	0.0	.0	0.	0.	0.
	WEIGHTED AVE.		23.22	.0468	75.	240.	775.

TABLE 42. ANNUAL CONTROL COSTS - STORM AREAS

NO	URBANIZED AREA	KEY CTY	EQN. (76) COEFS. k	EQN. (76) COEFS. β	CONTROL COST ($/ACRE) 25%	50%	75%
1	AJAX	7	10.24	.0380	26.	68.	177.
2	AURORA	7	9.69	.0390	25.	65.	167.
3	BARRIE	7	16.54	.0393	44.	118.	316.
4	BELLEVILLE	17	5.81	.0369	15.	37.	92.
5	BRAMPTON	7	8.41	.0377	22.	55.	142.
6	BRANTFORD	38	7.53	.0379	19.	50.	129.
7	BURLINGTON	7	11.11	.0382	29.	75.	195.
8	CHATHAM	38	4.59	.0369	12.	29.	73.
9	CHINGUACOUSY	7	11.34	.0383	30.	77.	201.
10	COBOURG	17	14.38	.0389	38.	101.	267.
11	DUNDAS	7	19.00	.0398	51.	139.	377.
12	ETOBICOKE	7	11.14	.0383	29.	76.	197.
13	GALT	7	18.99	.0397	51.	138.	373.
14	GEORGETOWN	7	20.17	.0401	55.	150.	408.
15	GUELPH	7	15.48	.0390	41.	109.	289.
16	HAMILTON	7	4.21	.0362	10.	26.	63.
17	KINGSTON	17	5.97	.0369	15.	38.	95.
18	KITCH.-WATERLOO	7	12.32	.0383	32.	84.	218.
19	LEAMINGTON	38	7.67	.0381	20.	52.	134.
20	LINDSAY	17	12.90	.0387	34.	89.	235.
21	LONDON	38	7.48	.0375	19.	49.	125.
22	MARKAM	7	11.24	.0383	29.	76.	199.
23	MIDLAND	7	5.26	.0363	13.	32.	80.
24	MISSISSAUGA	7	10.58	.0382	28.	75.	199.
25	NEWMARKET	7	11.24	.0383	29.	76.	199.
26	NIAGRA FALLS	38	3.82	.0362	9.	23.	58.
27	NORTH BAY	41	9.20	.0418	26.	74.	211.
28	OAKVILLE	7	12.00	.0385	31.	82.	215.
29	ORILLIA	7	19.69	.0395	53.	142.	381.
30	OSHAWA	7	9.29	.0377	24.	61.	157.
31	OWEN SOUND	7	7.10	.0371	18.	45.	114.
32	PETERBOROUGH	17	15.90	.0395	43.	115.	308.
33	PICKERING	7	15.72	.0393	42.	112.	299.
34	PORT COLBOURNE	38	14.19	.0395	38.	102.	274.
35	PORT ERIE	38	8.53	.0381	22.	57.	148.
36	PRESTON	7	17.85	.0394	48.	128.	342.
37	RICHMOND HILL	7	12.68	.0386	33.	87.	230.
38	ST. CATHARINES	38	4.62	.0368	12.	29.	73.
39	ST. THOMAS	38	4.31	.0364	11.	27.	66.
40	SARINA	36	5.83	.0372	15.	37.	95.
41	SLT. STE. MARIE	41	10.89	.0421	31.	89.	256.
42	SCARBOROUGH	7	6.31	.0371	16.	40.	102.
43	SIMCOE	38	9.20	.0382	24.	62.	161.
44	STRATFORD	7	22.49	.0398	61.	164.	445.
45	SUDBURY	41	9.63	.0422	28.	79.	228.
46	THUNDER BAY	41	4.80	.0407	13.	37.	102.
47	TORONTO	7	13.35	.0388	35.	93.	244.
48	TRENTON	17	17.04	.0397	46.	124.	334.
49	WALLACEBURG	38	6.05	.0375	15.	40.	101.
50	WELLAND	38	5.96	.0372	15.	38.	97.
51	WHITBY	7	17.42	.0393	47.	124.	331.
52	WINDSOR	38	5.31	.0372	13.	34.	87.
53	WOODSTOCK	38	16.16	.0399	44.	119.	323.
54	YORK	7	7.21	.0373	18.	47.	119.
55	YORK, EAST	7	6.14	.0370	15.	39.	99.
56	YORK, NORTH	7	11.88	.0385	31.	81.	213.
	WEIGHTED AVE.		9.95	.0386	26.	68.	180.

TABLE 43. ANNUAL CONTROL COSTS - UNSEWERED AREAS

NO	URBANIZED AREA	REF CTY	EQN. (76) COEFS. k	β	CONTROL COST ($/ACRE) 25%	50%	75%
1	AJAX	7	2.69	.0353	7.	16.	38.
2	AURORA	7	2.78	.0354	7.	16.	40.
3	BARRIE	7	2.62	.0353	6.	15.	37.
4	BELLEVILLE	17	3.01	.0355	7.	18.	43.
5	BRAMPTON	7	3.85	.0361	9.	23.	58.
6	BRANTFORD	36	3.50	.0361	9.	21.	52.
7	BURLINGTON	7	3.34	.0357	8.	20.	49.
8	CHATHAM	36	3.26	.0361	8.	20.	49.
9	CHINGUACOUSY	7	3.58	.0359	9.	22.	53.
10	COBOURG	17	2.48	.0351	6.	14.	34.
11	DUNDAS	7	2.60	.0353	6.	15.	37.
12	ETOBICOKE	7	3.49	.0359	9.	21.	52.
13	GALT	7	2.69	.0353	6.	16.	38.
14	GEORGETOWN	7	2.61	.0353	6.	15.	37.
15	GUELPH	7	2.85	.0354	7.	17.	40.
16	HAMILTON	7	0.0	.0	0.	0.	0.
17	KINGSTON	17	0.0	.0	0.	0.	0.
18	KITCH.-WATERLOO	7	3.66	.0358	9.	22.	54.
19	LEAMINGTON	36	2.18	.0352	5.	13.	31.
20	LINDSAY	17	2.42	.0351	6.	14.	34.
21	LONDON	36	3.21	.0356	8.	19.	46.
22	MARKAM	7	2.60	.0353	6.	15.	37.
23	MIDLAND	7	3.17	.0353	8.	18.	45.
24	MISSISSAUGA	7	3.35	.0358	8.	20.	49.
25	NEWMARKET	7	2.67	.0354	6.	16.	38.
26	NIAGRA FALLS	36	2.95	.0357	7.	18.	43.
27	NORTH BAY	41	3.45	.0391	9.	24.	65.
28	OAKVILLE	7	3.10	.0356	8.	18.	45.
29	ORILLIA	7	2.95	.0353	7.	17.	42.
30	OSHAWA	7	4.22	.0361	10.	26.	63.
31	OWEN SOUND	7	2.92	.0353	7.	17.	41.
32	PETERBOROUGH	17	2.31	.0351	6.	13.	32.
33	PICKERING	7	2.53	.0353	6.	15.	36.
34	PORT COLBOURNE	36	2.51	.0352	6.	15.	35.
35	PORT ERIE	36	2.49	.0352	6.	15.	35.
36	PRESTON	7	2.79	.0353	7.	16.	39.
37	RICHMOND HILL	7	2.61	.0353	6.	15.	37.
38	ST. CATHARINES	36	3.50	.0361	9.	21.	53.
39	ST. THOMAS	36	2.57	.0352	6.	15.	36.
40	SARINA	36	0.0	.0	0.	0.	0.
41	SLT. STE. MARIE	41	3.03	.0386	8.	21.	55.
42	SCARBOROUGH	7	3.56	.0359	9.	21.	53.
43	SIMCOE	36	2.57	.0352	6.	15.	36.
44	STRATFORD	7	3.12	.0353	8.	18.	44.
45	SUDBURY	41	2.69	.0387	7.	19.	49.
46	THUNDER BAY	41	2.64	.0390	7.	19.	49.
47	TORONTO	7	0.0	.0	0.	0.	0.
48	TRENTON	17	2.39	.0351	6.	14.	33.
49	WALLACEBURG	36	2.19	.0352	5.	13.	31.
50	WELLAND	36	2.49	.0352	6.	14.	35.
51	WHITBY	7	2.79	.0353	7.	16.	39.
52	WINDSOR	36	2.68	.0357	7.	16.	39.
53	WOODSTOCK	36	2.49	.0352	6.	14.	35.
54	YORK	7	0.0	.0	0.	0.	0.
55	YORK, EAST	7	0.0	.0	0.	0.	0.
56	YORK, NORTH	7	0.0	.0	0.	0.	0.
	WEIGHTED AVE.		2.96	.0360	7.	18.	44.

Because of this definition, the number of overflows may increase with an increase in treatment rate as shown in Figure 25. If the treatment rate is high enough to deplete storage after the first overflow, then the event is over. When storage is utilized later a new event starts, and any overflow occurring in this event is considered separate from the first overflow. Thus, the number of overflow events was increased from one to two events, even though the treatment rate was increased.

The number of overflow events appears to provide a more meaningful parameter if the event is defined differently than the definition used by STORM. The overflows shown in case 2 in Figure 25, should be considered as a single event since they occur so closely together. Based on the U.S. assessment, a storm event terminates after 12 hours of no precipitation [2]. Using this definition, the approximate relationship between overflow events and percent volume control is derived as shown in Figure 26, for Burlington and Kingston. Thus, a rough approximation of the relationship between percent R and overflow events (OE) is $d(OE)/dR = -1$.

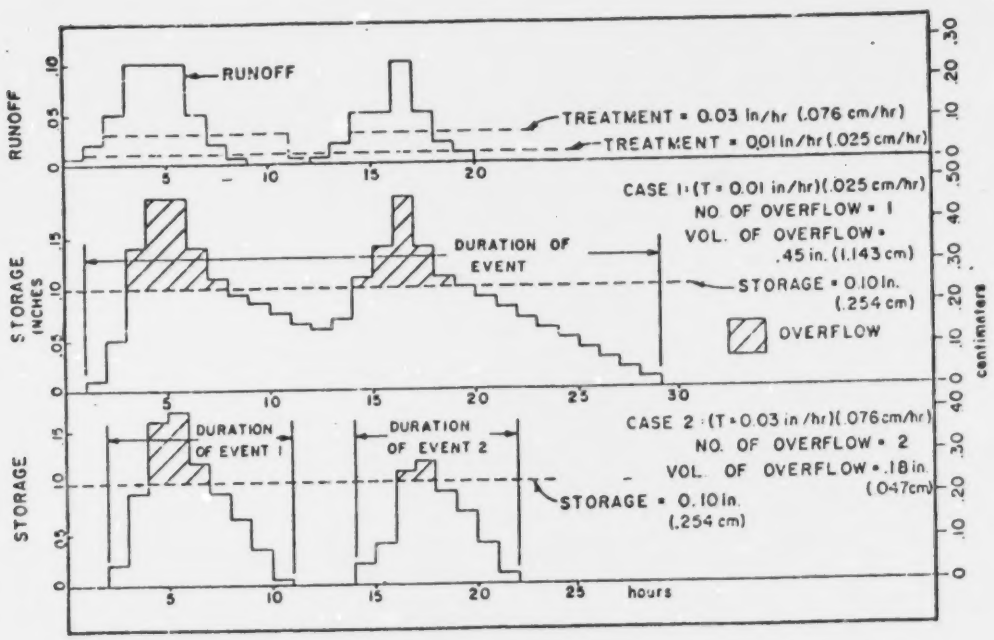

RUNOFF
RUNOFF
TREATMENT = 0.03 in/hr (.076 cm/hr)
TREATMENT = 0.01 in/hr (.025 cm/hr)
CASE 1: (T = 0.01 in/hr)(.025 cm/hr)
NO. OF OVERFLOW = 1
VOL. OF OVERFLOW = .45 in. (1.143 cm)
DURATION OF EVENT
STORAGE = 0.10 in. (.254 cm)
OVERFLOW
STORAGE INCHES
CASE 2: (T = 0.03 in/hr)(.076 cm/hr)
NO. OF OVERFLOW = 2
VOL. OF OVERFLOW = .18 in. (.047cm)
DURATION OF EVENT 1
DURATION OF EVENT 2
STORAGE = 0.10 in. (.254 cm)
STORAGE
hours
centimeters

FIGURE 25. EFFECT OF STORAGE AND TREATMENT CAPACITY ON NUMBER OF OVERFLOW EVENTS.

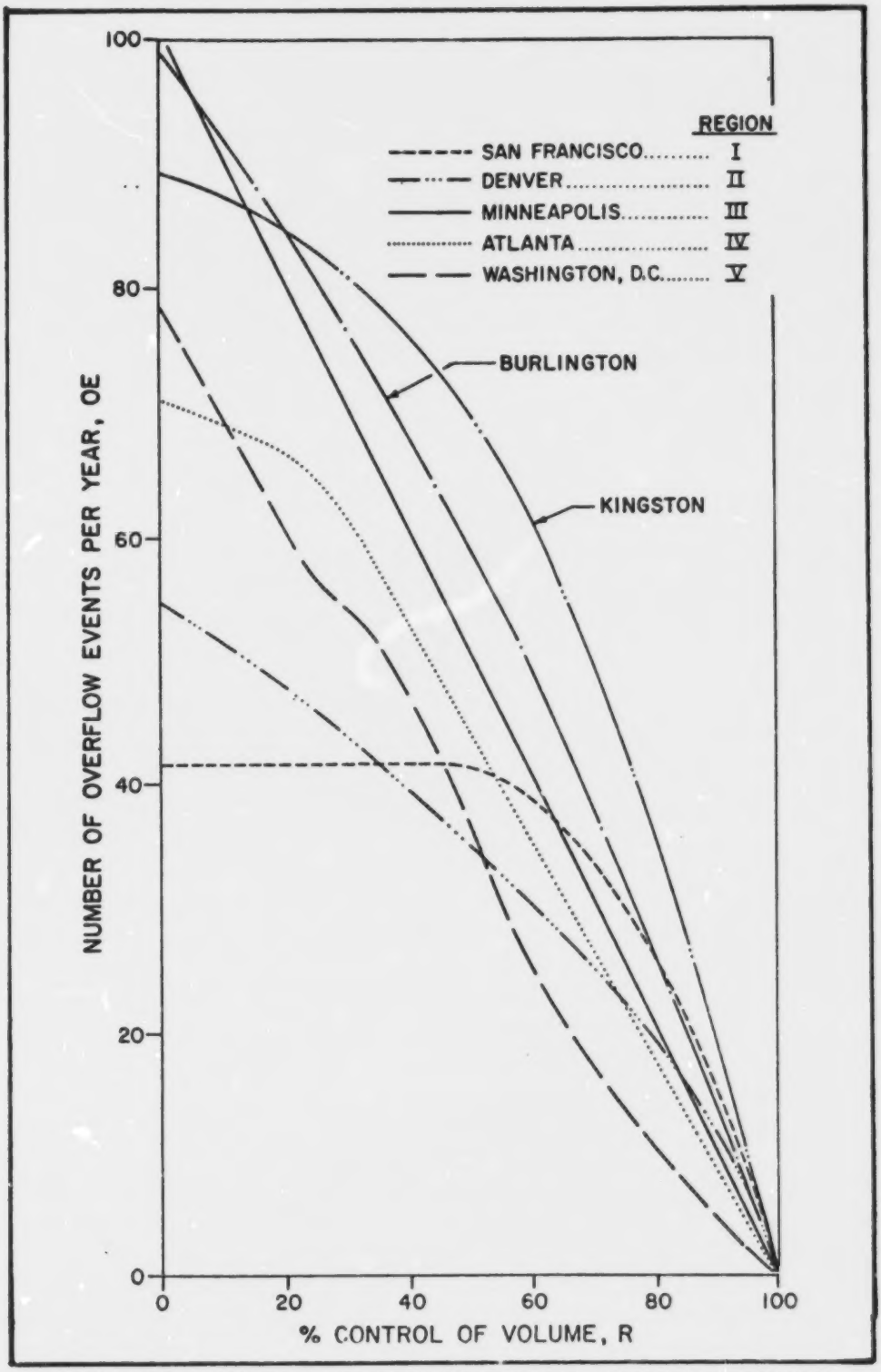


FIGURE 26. NUMBER OF OVERFLOW EVENTS vs PERCENT CONTROL.

5.5 The Overall Cost Assessment

5.5.1 Overall results

General results thus far are summarized in Tables 44, 45, 46, 47 and 48.

The only remaining problem is to estimate the province wide costs for 25, 50, and 75 percent control. As a first approximation, assume that an overall 25 percent control level is achieved by 25 percent control on the combined (A_1), storm (A_2) and unsewered (A_3) areas. Thus, the approximate total annual costs, TAC, are:

$$\begin{aligned}(TAC)_{25} &= 75A_1 + 26A_2 + 7A_3 \\ &= 75\ (71{,}000) + 26\ (210{,}000) + 7\ (114{,}000) \\ &= \$11{,}583{,}000/yr\end{aligned} \tag{77}$$

Likewise,

$$(TAC)_{50} = \$33{,}372{,}000/yr \tag{78}$$

$$(TAC)_{75} = \$97{,}841{,}000/yr \tag{79}$$

Recall that the cost of wet-weather control using secondary facilities is:

$$Z_s = ke^{\beta R_1} \tag{80}$$

where: Z_s = annual cost, dollars per acre,

k β = constants, and

R_1 = percent BOD removal ($0 \leq R_1 \leq 85$).

The cost of wet-weather control in terms of pounds of pollutant removed, w, is:

$$Z_s = ke^{\beta} \left(\frac{100}{M}\right) w \tag{81}$$

The marginal cost of BOD removal is:

$$\frac{dZ_s}{dw} = \frac{100\ \beta\ k}{M} e^{\frac{100\ \beta\ w}{M}} \tag{82}$$

However, the optimum mix of control of storm runoff from combined storm and unsewered areas is found by equating marginal costs. Using

TABLE 44. GENERAL INFORMATION

Total Urbanized Area	=	586,000 acres (237,000 ha)
Total Population Area	=	4,720,000 persons
Average Population Density	=	8.07 persons/acre (19.9 persons/ha)
Average Precipitation	=	32.75 inches/year (83.2 cm/hr)

TABLE 45. LAND USE BY TYPE OF USE

Use	1,000 Acres	(ha)
Undeveloped	191	(77)
Residential	208	(85)
Commercial	40	(16)
Industrial	55	(22)
Other	92	(37)
Total	586	(237)

TABLE 46. LAND USE AND POPULATION BY TYPE OF SEWERAGE SYSTEM

	1,000 Acres	(ha)	1,000 Persons	Developed Population Density Persons/ Acre	(ha)
Undeveloped	191	(77)	0	0	
Combined	71	(29)	1,773	24.9	(61.5)
Storm	210	(85)	2,485	11.9	(29.4)
Unsewered	114	(46)	468	4.1	(10.1)
	586	(237)	4,726	12.0	(29.7)

TABLE 47. QUANTITY AND QUALITY OF SEWAGE AND STORM WATER RUNOFF

Sewerage System	Flow: in/yr (cm/yr) Sewage		Storm Runoff		Quality: Annual Pounds of BOD/Acre (kg/ha) Sewage		Storm Runoff	
Combined	33.4	(84.8)	16.2	(41.1)	1,545	(1,733)	137.0	(153.7)
Storm	15.9	(40.4)	12.8	(32.5)	736	(826)	25.7	(28.8)
Unsewered	5.5	(14.0)	9.5	(24.1)	255	(286)	21.3	(23.9)
	16.1	(40.9)	12.5	(31.8)	743	(834)	44.5	(49.9)

TABLE 48. ANNUAL CONTROL COSTS PER UNIT OF DEVELOPED URBAN AREA: $/ACRE ($/ha)

Sewerage System	Level of Control, % of Total 25		50		75		Coefficients K	B
Combined	75	(185)	240	(593)	775	(1915)	23.2	0.047
Storm	26	(64)	68	(168)	180	(445)	9.9	0.039
Unsewered	7	(17)	18	(44)	44	(109)	3.0	0.036

equation (82) with the subscript (1) denoting combined, (2) denoting storm, and (3) denoting unsewered, yields:

$$\frac{100\ \beta_1\ k_1}{M_1}\ e^{\frac{100\ \beta_1\ w_1}{M_1}} = \frac{100\ \beta_2\ k_2}{M_2}\ e^{\frac{100\ \beta_2\ w_2}{M_2}}$$

$$= \frac{100\ \beta_3\ k_3}{M_3}\ e^{\frac{100\ \beta_3\ w_3}{M_3}} \qquad (83)$$

If the above approximation is used, and marginal costs are compared for say, 50 percent BOD removal, one obtains:

$$MC_1 = \frac{100(0.047)\ (23.2)}{137.0}\ e^{100(0.047)\ (0.5)} \qquad (84)$$

= \$8.35/lb BOD (\$18.39/kg BOD)

$$MC_2 = \frac{100(0.039)\ (9.9)}{25.7}\ e^{100(0.039)\ (0.5)} \qquad (85)$$

= \$10.56/lb BOD (\$23.26/kg BOD)

$$MC_3 = \frac{100(0.036)\ (3.0)}{21.3}\ e^{100(0.036)\ (0.5)} \qquad (86)$$

= \$3.07/lb BOD (\$6.76/kg BOD)

This result indicates that, to achieve 50 percent control, unsewered and combined sewer areas should be controlled more intensively due to their relatively low marginal costs. Storm sewer areas should be the least intensively controlled due to their relatively high marginal cost.

The correct solution can be found by solving for w_1 and w_3 as functions of w_2, i.e.,

$$w_1 = a_{1\,2} + b_{1\,2}\ w_2 \qquad (87)$$

$$w_2 = a_{3\,2} + b_{3\,2}\ w_2 \qquad (88)$$

where: $a_{1\,2} = \frac{M_1}{100\beta_1} \ln\left[\left(\frac{\beta_2}{\beta_1}\right)\left(\frac{k_2}{k_1}\right)\left(\frac{M_1}{M_2}\right)\right]$

$$a_{3\,2} = \frac{M_3}{100\beta_3} \ln\left[\left(\frac{\beta_2}{\beta_3}\right)\left(\frac{k_2}{k_3}\right)\left(\frac{M_3}{M_2}\right)\right]$$

$$b_{1\,2} = \left(\frac{\beta_2}{\beta_1}\right)\left(\frac{M_1}{M_2}\right)$$

$$b_{3\,2} = \left(\frac{\beta_2}{\beta_3}\right)\left(\frac{M_3}{M_2}\right)$$

M_1, M_2, M_3, β_1, β_2, β_3, k_1, k_2, k_3, w_1, w_2, w_3 are as defined earlier.

The total wet-weather pollution load, WP, is

$$WP = \sum_{i=1}^{3} M_i A_i \tag{89}$$

where: M_i = annual pounds per acre from i^{th} area, and
A_i = area of i^{th} area.

Let ρ denote the proportion of WP that one wishes to control. Then, the optimum solution for a given ρ is found by substituting equations (87) and (88) into (89) or

$$\rho(WP) = w_1 A_1 + w_2 A_2 + w_3 A_3 \tag{90}$$

$$\rho(WP) = (a_{1\,2} + b_{1\,2} w_2)A_1 + w_2 A_2 + (a_{3\,2} + b_{3\,2} w_2)A_3 \tag{91}$$

or

$$w_2^* = \frac{\rho(WP) - a_{1\,2} A_1 - a_{3\,2} A_3}{b_{1\,2} A_1 + A_2 + b_{3\,2} A_3} \tag{92}$$

Knowing w_2^*, the optimum pounds of pollutant removal for area 2, one can find the optimum levels of pollutant removed for areas 1 and 3, w_1^*, and w_3^*, by substituting into equations (87) and (88).

The results of the Ontario assessment indicate the values for the parameters shown earlier. Using these data, one obtains

a) $WP = M_1 A_1 + M_2 A_2 + M_3 A_3$

$= 137.0(71,000) + 25.7(210,000) + 21.3(114,000)$

$WP = 17,552,000$ lbs BOD/yr (7,969,000 kg BOD/yr)

b) $a_{1\,2}$ and $a_{3\,2}$

$$a_{1\,2} = \frac{M_1^{\beta}}{100\beta_1} \ln\left[\left(\frac{\beta_2}{\beta_1}\right)\left(\frac{k_2}{k_1}\right)\left(\frac{M_1}{M_2}\right)\right]$$

$$= \frac{137.0}{100(0.047)} \ln\left[\left(\frac{0.039}{0.047}\right)\left(\frac{9.9}{23.2}\right)\left(\frac{137.0}{25.7}\right)\right]$$

$$a_{1\,2} = 18.52$$

Similarly,

$$a_{3\,2} = 6.43$$

c) $b_{1\,2}$ and $b_{3\,2}$

$$b_{1\,2} = \left(\frac{\beta_2}{\beta_1}\right)\left(\frac{M_1}{M_2}\right)$$

$$= \left(\frac{0.039}{0.047}\right)\left(\frac{137.0}{25.7}\right)$$

$$b_{1\,2} = 4.42$$

Similarly,

$$b_{3\,2} = 0.898$$

Thus,

$$w_2^* = \frac{\rho(17{,}552{,}000) - (18.52)(71{,}000) - (6.43)(114{,}000)}{4.42(71{,}000) + 210{,}000 + 0.898(114{,}000)} \qquad (93)$$

or

$$w_2^* = 28.03\rho - 3.27 \qquad (94)$$

Then, substituting into equations (87) and (88) to find w_1^* and w_3^* yields:

$$w_1^* = 123.89\rho + 4.07 \qquad (95)$$

$$w_3^* = 25.17\rho + 3.49 \qquad (96)$$

Let $(R_i^*)_\rho = 100\ (w_i^*)_\rho / M_i$ denote the optimum percent control of the i^{th} source for control level, ρ. Then,

$$(R_1^*)_\rho = \frac{100(123.89\rho + 4.07)}{137.0} = 90.4\rho + 3.0 \qquad (97)$$

$$(R_2^*)_\rho = \frac{100(28.03\rho - 3.27)}{25.7} = 109.1\rho - 12.7 \quad (98)$$

$$(R_3^*)_\rho = \frac{100(25.17\rho + 3.49)}{21.3} = 118.2\rho + 16.4 \quad (99)$$

Let $\lambda_i = A_i M_i / WP$ for i = 1, 2, 3 denote the proportion of total pollutant load from the three areas.

$$\lambda_1 = \frac{137.0(71,000)}{17,552,000} = 0.554 \quad (100)$$

$$\lambda_2 = \frac{25.7(210,000)}{17,552,000} = 0.308 \quad (101)$$

$$\lambda_3 = \frac{21.3(114,000)}{17,552,000} = \frac{0.138}{1.000} \quad (102)$$

The optimum percent control of 25, 50 and 75 percent is shown in Table 49.

TABLE 49. OPTIMUM PERCENT CONTROL FOR SPECIFIED OVERALL PERCENT CONTROL

Level of Control	Optimum Level of Control R_1^*	R_2^*	R_3^*	$\sum_{i=1}^{3} R_1 \lambda_i$
0.25	25.6	14.6	46.0	25.0
0.50	48.2	41.9	75.5	50.0
0.75	73.8	72.6	85.0	75.0

Knowing $(R_i)_\rho$, one can find the cost per acre by simply substituting into equation (80), i.e.,

$$Z_s = ke^{\beta R_1} \quad (103)$$

to obtain the optimum annual cost per acre as shown in Table 50. Thus, the optimum annual control costs are shown in Table 51.

5.5.2 Potential savings due to multipurpose planning

The cost of wet-weather quality control can be reduced by integrating this purpose with dry-weather treatment plants and/or storage reservoirs for storm water quantity control. Dry-weather sewage treatment

TABLE 50. OPTIMUM ANNUAL COST PER ACRE FOR SPECIFIED PERCENT CONTROL

Type of Sewerage System	Optimal Annual Cost/Acre (ha) for Specified % Control 25	50	75
Combined	77(190)	224(553)	745(1,841)
Storm	17(42)	51(126)	168(415)
Unsewered	16(40)	45(111)	64(158)

TABLE 51. OPTIMUM ANNUAL CONTROL COSTS

Level of Control	Optimal Annual Cost: $/yr
25	10,861,000
50	31,744,000
75	95,471,000

plants are designed to handle the peak flow anticipated 10 to 15 years after construction. The full capacity of these plants is seldom utilized because peak flows occur infrequently and also because additional capacity is frequently added before the actual flow approaches the design capacity of the plant. Provision of storage to equalize peak flows can greatly enhance the effective capacity of the existing treatment units. Utilization of this excess capacity can reduce the treatment capacity needed for wet-weather quality control. Similarly, utilization of storage available for wet-weather quantity control can result in reducing the storage and treatment requirements for wet-weather quality control.

Preliminary results from the U.S. assessment, wherein excess capacity of 10 mgd in a 20 mgd plant was assumed and the city needed to store the excess (over natural) runoff for a two-year, 24-hour storm, indicated that it was possible to achieve significant savings due to multipurpose planning [2]. For these assumed conditions, the savings as compared to the single purpose venture are as shown below:

Level of Control	Savings as % of Single Purpose Control Costs
25%	54%
50%	50%
75%	30%

These results are suggestive only. Specific studies are needed to refine these rough estimates.

5.5.3 Tertiary treatment versus wet-weather treatment

The optimum mix of tertiary treatment and wet-weather control can be found by equating the marginal cost of tertiary treatment with the marginal cost of wet-weather pollution control. The estimated total annual incremental cost of a tertiary treatment plant is [2]:

$$C_{tert} = 87{,}000\ D^{0.787} \tag{104}$$

where: C_{tert} = total annual incremental cost of tertiary treatment plant, dollars per year, and

D = plant size, mgd.

Assume a 25 mgd plant. Then, C_{tert} = \$1,096,000 per year. The plant is assumed to increase the BOD removal from 85 percent to 95 percent or about 0.017 pounds (7.71 g) per capita-day or 1,550,000 pounds (704,000 kg) per year for the city of 250,000 people. Thus, the unit cost of tertiary treatment, c_{tert}, is \$0.71 per pound (\$1.56 per kg) of BOD removed.

Equating the marginal cost of wet-weather control to the unit cost of tertiary treatment yields:

$$c_{tert} = \frac{100\beta\ k}{M} e^{\frac{100\beta\ w}{M}} \tag{105}$$

or

$$w^* = \frac{M}{100\beta} \ln \left[\frac{c_{ert}(M)}{100\beta\ (K)}\right] \tag{106}$$

where: w^* = optimum pounds of wet-weather pollution to control prior to using tertiary treatment.

The optimum percent control in terms of R_1 is:

$$R_1 = \max \left(\frac{1}{\beta} \ln\left[\frac{c_{tert}^{(M)}}{100\beta\,(k)}\right], 0\right) \qquad (107)$$

The overall average BOD loading per acre, $\overline{M}$, is

$$\overline{M} = \frac{WP}{(A_1 + A_2 + A_3)} = \frac{17,552,000}{395,000}$$

$$\overline{M} = 44.5 \text{ lb BOD/acre } (49.9 \text{ kg/ha})$$

Then,

$$R_1 = \max \left[\frac{1}{0.044} \ln \frac{0.71(44.5)}{100(0.044)(3.60)}, 0\right] = 15.7 \qquad (108)$$

Thus, for these assumed conditions, approximately 16 percent of the wet-weather pollution should be controlled prior to initiating tertiary treatment. While these results are for one specific set of assumptions, they do suggest that it is highly desirable to do this tradeoff analysis before committing a community to tertiary treatment.

5.6 Summary

The purpose of this assessment was to evaluate the cost of controlling varying levels of wet-weather pollution emanating from the 4,720,000 people in 56 cities in Ontario. Reliable procedures for assessing storm water pollution were not yet available. Thus, a considerable amount of developmental effort was expended in devising such procedures. Major results are presented, by item, in the next paragraphs.

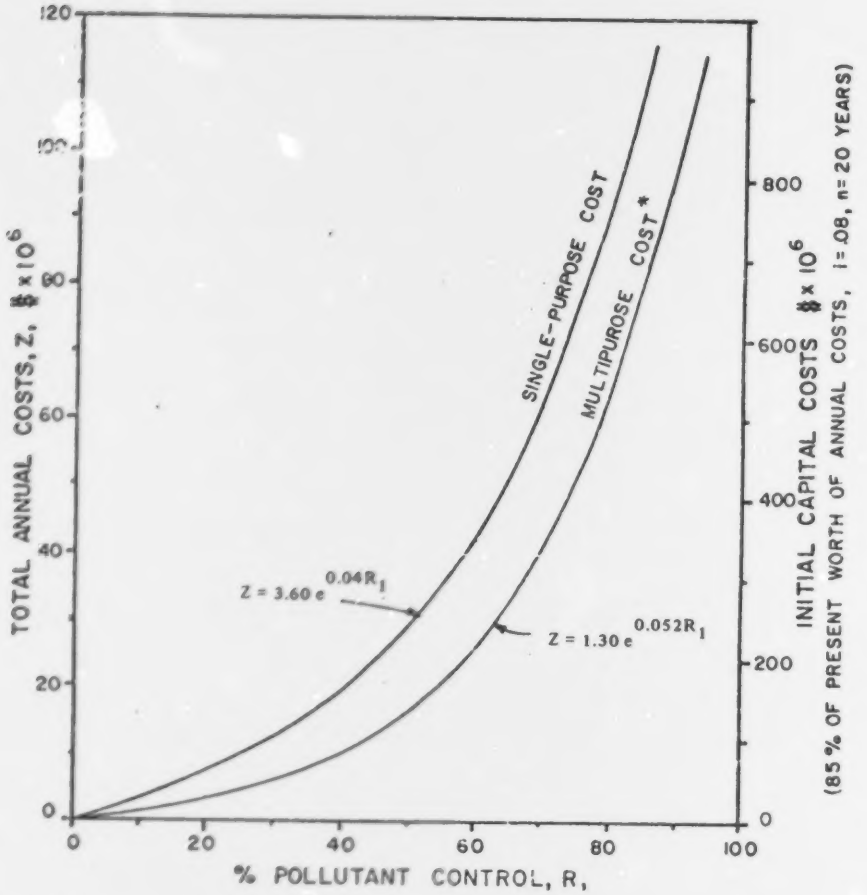
1) Land Use - Using a definition of urbanized areas which includes population densities as low as one person per acre leads to inclusion of the relatively large amount of land which is undeveloped (about one-third of the total land). Residential development utilizes the majority of the developed land.
2) Type of Sewerage System - Very limited data exist on the population and area served by various types of storm drainage systems. Population served by combined, storm, and unsewered areas was derived by assuming that the highest density areas were served by combined sewers, the intermediate level by storm sewers, and the

lowest density areas were unsewered. The transition points were identified using available data on areas served by the three systems. This method would tend to overestimate the population served by combined sewers.

3) Quantity of Storm Water - An average of 28.6 inches of water per year leaves Ontario cities, of which 12.5 inches comprise storm water runoff. Annual storm water runoff volumes exceed sewage flows in low density urban areas. Urban runoff is significant relative to sewage flows in low density urban development. Thus, on a volumetric basis, urban runoff is significant relative to sewage flows.

4) Quality of Storm Water - Storm water pollution loads approach wastewater effluent loads after secondary treatment has been installed. The exact quantity of storm water pollution remains unknown due to lack of sufficient data. Numerous assumptions were needed to develop a general pollution loading equation. There seems to be general agreement that combined sewer overflows are much more serious than storm water runoff. However, the results of this assessment indicate relatively low loadings of storm water pollutants (about one-half of the load coming from secondary treatment plant effluent). Only through carefully conducted sampling programs can these estimates be refined.

5) Total Single-Purpose Control Costs - Relatively detailed studies in four Ontario cities provided the basis for evaluating storage-treatment alternatives for wet-weather control. One year of hourly data was simulated to predict the performance of various storage-treatment configurations. These results were put in analytical form to expedite extrapolation to all urbanized areas. These results are combined with data on the cost of storage and treatment to derive the optimum mix of storage and treatment to use to obtain a given level of control. The final result is shown in Figure 27. A striking feature of the curve is that it bends upward (convex) indicating increasing incremental costs (particularly at higher levels of control). The primary reason the curve has this shape is due to the disproportionately larger amounts of storage and treatment required to control the larger storms.



*Assumes management plan integrating dry-weather quality control, wet-weather quality control, and wet-weather quantity control.

FIGURE 27. TOTAL ANNUAL AND INITIAL CAPITAL COSTS FOR VARIOUS LEVELS OF WET-WEATHER POLLUTION CONTROL IN ONTARIO

6) Total Multiple-Purpose Control Costs - Significant savings can be realized if one integrates dry- and wet-weather treatment and storage for quality as well as quantity control. The lower curve in Figure 27 indicates the cost of storm water quality control in an integrated system. This result suggests that the potential savings are significant enough to warrant further study in evaluating storm water systems.

7) Tertiary Treatment versus Storm Water Quality Management - A comparison of the marginal costs of tertiary treatment of sewage for further BOD control with initiating control of wet-weather quality

indicates that one should initiate some level of wet-weather quality control prior to using tertiary treatment. Of course, a different result would occur if nutrient control is used instead of BOD control. Nevertheless, the relative low marginal costs of wet-weather control at low levels of control indicate that it should be given serious consideration as an alternative to tertiary treatment.

5.7 List of Variables

a	coefficient (inches per hour)
A_1	combined sewer area
A_2	storm sewer area
A_3	unsewered area
A_{tot}	total developed area
AR	annual runoff (inches per year)
b	coefficient (inches per hour)
β	coefficient in cost equation
c	coefficient (percent R^{-1})
c_{tert}	unit cost of tertiary treatment (dollars per pound)
c_S	unit cost of storage (annual dollars per acre-inch)
c_T	unit cost of treatment (annual dollars per inch per hour)
C_{tert}	Total annual incremental cost of tertiary treatment plant (dollars per year)
d	coefficient ($inch^{-1}$)
D	plant size (mgd)
ENR	Engineering News Record Cost Index
η	treatment plant efficiency
f	coefficient $(percent\ R)^{-1}$
$f(R_1:S,T)$	Production function relating percent pollutant control (R_1) to storage (S) and treatment (T)
k	coefficient
K	coefficient
L	breakeven pipe length
λ_i	proportion of total pollutant load from i^{th} area
M	annual pounds of pollutant (pounds per acre-year)

$\bar{M}$	average annual pollutant loading (pounds per acre-year)
MC	marginal cost
MRS_{ST}	marginal rate of substitution of storage for treatment
OE	number of overflow events per year
PD	gross population density
PD_d	population density in developed portion of urban area
q	coefficient
R	percent runoff control
R_1	percent pollutant control
R_1^*	optimum percent of pollutant control prior to using tertiary treatment
$\bar{R}$	maximum percent pollutant control
ρ	proportion of WP which is controlled
s	coefficient
S	storage volume, inches
S*	optimum storage volume (inches)
T	treatment rate (inches per hour)
T*	optimum treatment rate (inches per hour)
T_1	treatment rate at which isoquant is parallel to the ordinate (inches per hour)
T_2	treatment rate at which isoquant intersects the abscissa (inches per hour)
TAC	total annual cost: $/year
w	annual pounds of pollutant removed
w*	optimum pounds of wet-weather pollutants to control prior to using tertiary treatment
WP	total wet-weather pollutant load (lbs/year)
y	coefficient
z	coefficient
Z	total annual cost (dollars per acre)
Z*	optimum total annual cost (dollars per acre)
Z_s	total annual cost for secondary control unit (dollars per acre

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APPENDIX I

GLOSSARY

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GLOSSARY

Antecedent conditions - Initial conditions in catchment as determined from hydrologic events prior to storm.

Biological treatment processes - Means of treatment in which bacterial or biochemical action is intensified to stabilize, oxidize, and nitrify the unstable organic matter present. Trickling filters, activated sludge processes, and lagoons are examples.

Catchment - Surface drainage area.

Combined sewage - Sewage containing both domestic sewage and surface water or storm water, with or without industrial wastes. Includes flow in heavily infiltrated sanitary sewer systems as well as combined sewer systems.

Combined sewer - a sewer receiving both intercepted surface runoff and municipal sewage.

Combined sewer overflow - Flow from a combined sewer in excess of the interceptor capacity that is discharged into a receiving water.

Conservative - Non-interacting substance, undergoing no kinetic reaction; examples are salinity, total dissolved solids, total nitrogen, total phosphorus.

Convective precipitation - Precipitation caused by lifting due to convective currents, as in thunderstorms.

Cyclonic precipitation - Precipitation caused by lifting associated with junctions of different air masses, as for instance, with most warm and cold fronts.

Depression storage - Amount of precipitation which can fall on an area without causing runoff.

Detention - The slowing, dampening, or attenuating of flows either entering the sewer system or within the sewer system by temporarily holding the water on a surface area, in a storage basin, or within the sewer itself.

Domestic sewage - Sewage derived principally from dwellings, business buildings, institutions, and the like. It may or may not contain groundwater.

Economies of scale - Unit costs decrease as output increases.

Equalization - The averaging (or method for averaging) of variations in flow and composition of a liquid.

Expansion path - Locus of points connecting numerous isoquants indicating the optimum combination of inputs.

First flush - The condition, often occurring in storm sewer discharges and combined sewer overflows, in which a disproportionately high pollution load is carried in the first portion of the discharge or overflow.

Frequency diagram - Curve which relates the number of occurrences of events to their magnitude.

Initial abstraction - Initial precipitation loss including interception and depression storage.

In-system - Within the physical confines of the sewer pipe network.

Interception - Initial loss of precipitation due to vegetation.

Isoquant Lines - Lines of equal cost.

Isoquants - Curves representing combinations of the inputs yielding the same amount of output.

Non-conservative - Substance undergoing kinetic interaction, assumed to be a first-order reaction; examples are biochemical oxygen demand (BOD), coliform bacteria, dissolved oxygen (DO).

Orographic precipitation - Precipitation caused by lifting of an air mass over mountains.

Orthophosphate - Phosphate that appears as $PO_4^{=}$, $HPO_4^{=}$ or H_2PO_4, i.e. is hydrolizable. Creates a growth response in algae.

Physical-chemical treatment process - Means of treatment in which the removal of pollutants is brought about primarily by chemical clarification in conjunction with physical processes. The process string generally,

includes preliminary treatment, chemical clarification, filtration, carbon adsorption, and disinfection.

Pollutant - Any harmful or objectionable material in, or change in physical characteristics of water or sewage.

Precipitation event - A precipitation event terminates if zero rainfall has been recorded for the previous specified time interval.

Primary treatment - Process which removes about 35 percent of the biochemical oxygen demand of the waste.

Retention - The prevention of runoff from entering the sewer system by storing on a surface area or in a storage basin.

Runoff coefficient - Fraction of rainfall that appears as runoff after subtracting depression storage and interception. Typically accounts for infiltration into ground and evaporation.

Sanitary sewer - A sewer that carries liquid and water-carried wastes from residences, commercial buildings, industrial plants, and institutions, together with relatively low quantities of ground, storm, and surface waters that are not admitted intentionally.

Secondary treatment - Process which removes about 90 percent of the biochemical oxygen demand of the waste.

Sewer - A pipe or conduit generally closed, but normally not flowing full, for carrying sewage or other waste liquids.

Sewerage - System of piping, with appurtenances, for collecting and conveying wastewaters from source to discharge.

Storm flow - Overland flow, sewer flow, or receiving stream flow caused totally or partially by surface runoff or snowmelt.

Storm sewer - A sewer that carries intercepted surface runoff, street wash and other wash waters, or drainage, but excludes domestic sewage and industrial wastes.

Storm sewer discharge - Flow from a storm sewer that is discharged into a receiving water.

Storm water - Water resulting from precipitation which either percolates into the soil, runs off freely from the surface, or is captured by storm sewer, combined sewer, and to a limited degree sanitary sewer facilities.

Surface runoff - Precipitation that falls onto the surfaces of roofs, streets, ground, etc., and is not absorbed or retained by that surface, thereby collecting and running off.

Tertiary treatment - Process which removes about 96 percent of the biochemical oxygen demand of the waste.

Urbanized area - Central city, or cities, and surrounding closely settled territory. Central city (cities) have population of 50,000 or more. Peripheral areas with population density of one person per acre or more are included. (United States city definition)

Urban runoff - Surface runoff from an urban drainage area that reaches a stream or other body of water or a sewer.

Wastewater - The spent water of a community.

APPENDIX II

MAPS OF AREAS OF DATA TABULATION

FOR SEVEN TEST CITIES IN ONTARIO

FIGURE 28. AREA OF DATA TABULATION IN BURLINGTON
(inside hatched line)

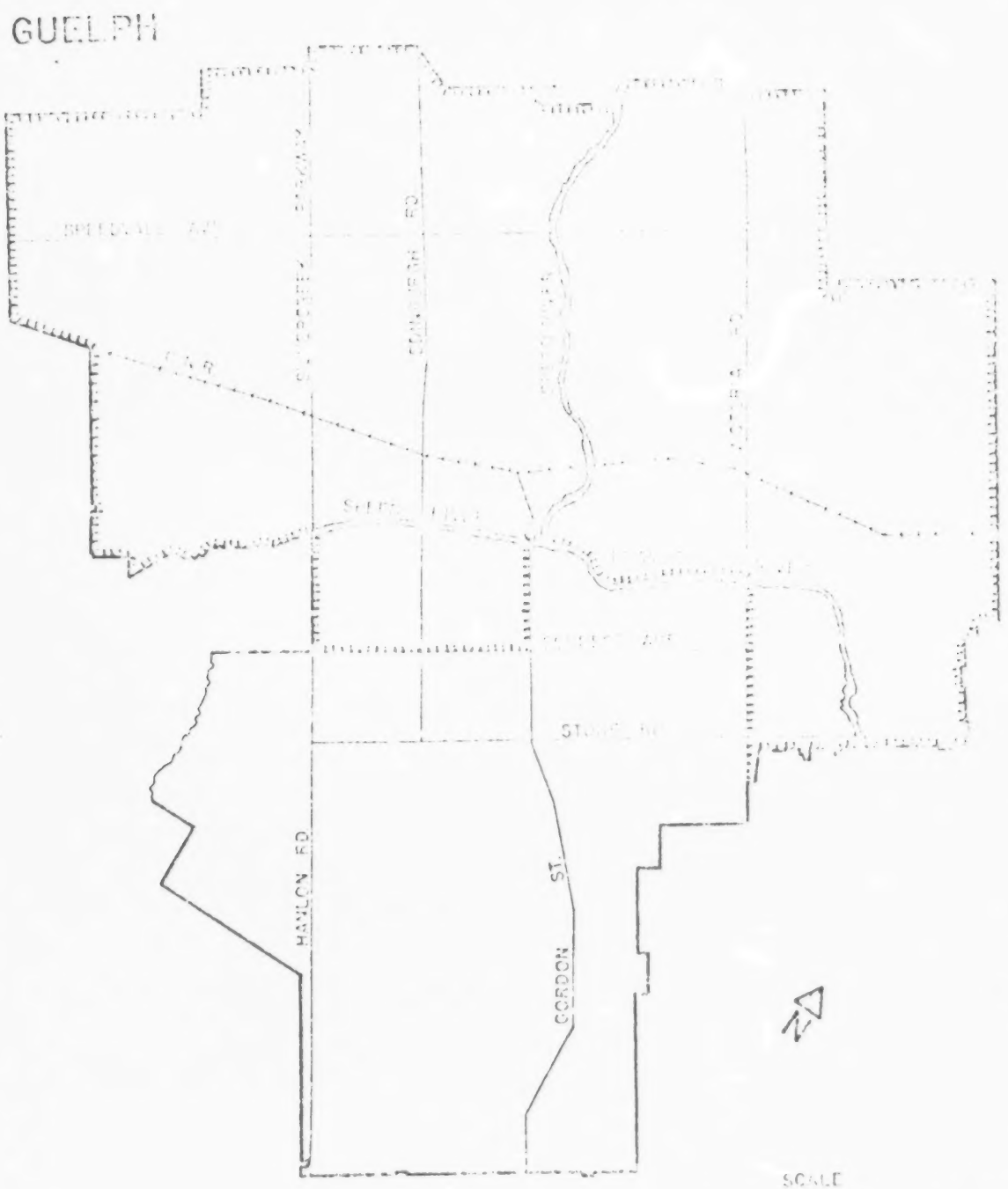

FIGURE 29. AREA OF DATA TABULATION IN GUELPH
(inside hatched line)

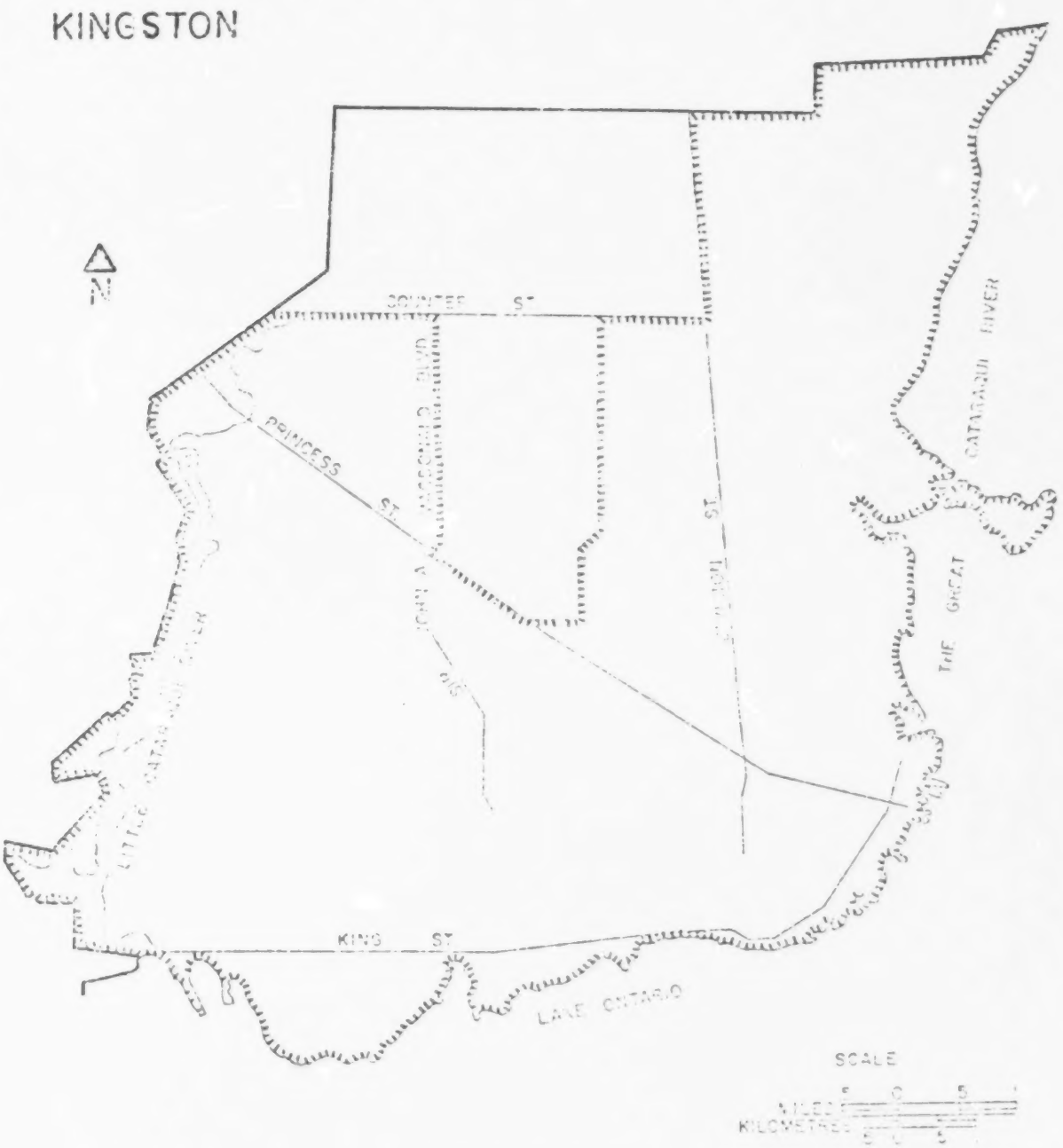

FIGURE 30. AREA OF DATA TABULATION IN KINGSTON
(inside hatched line)

FIGURE 31. AREA OF DATA TABULATION IN KITCHENER
(inside hatched line)

MILTON

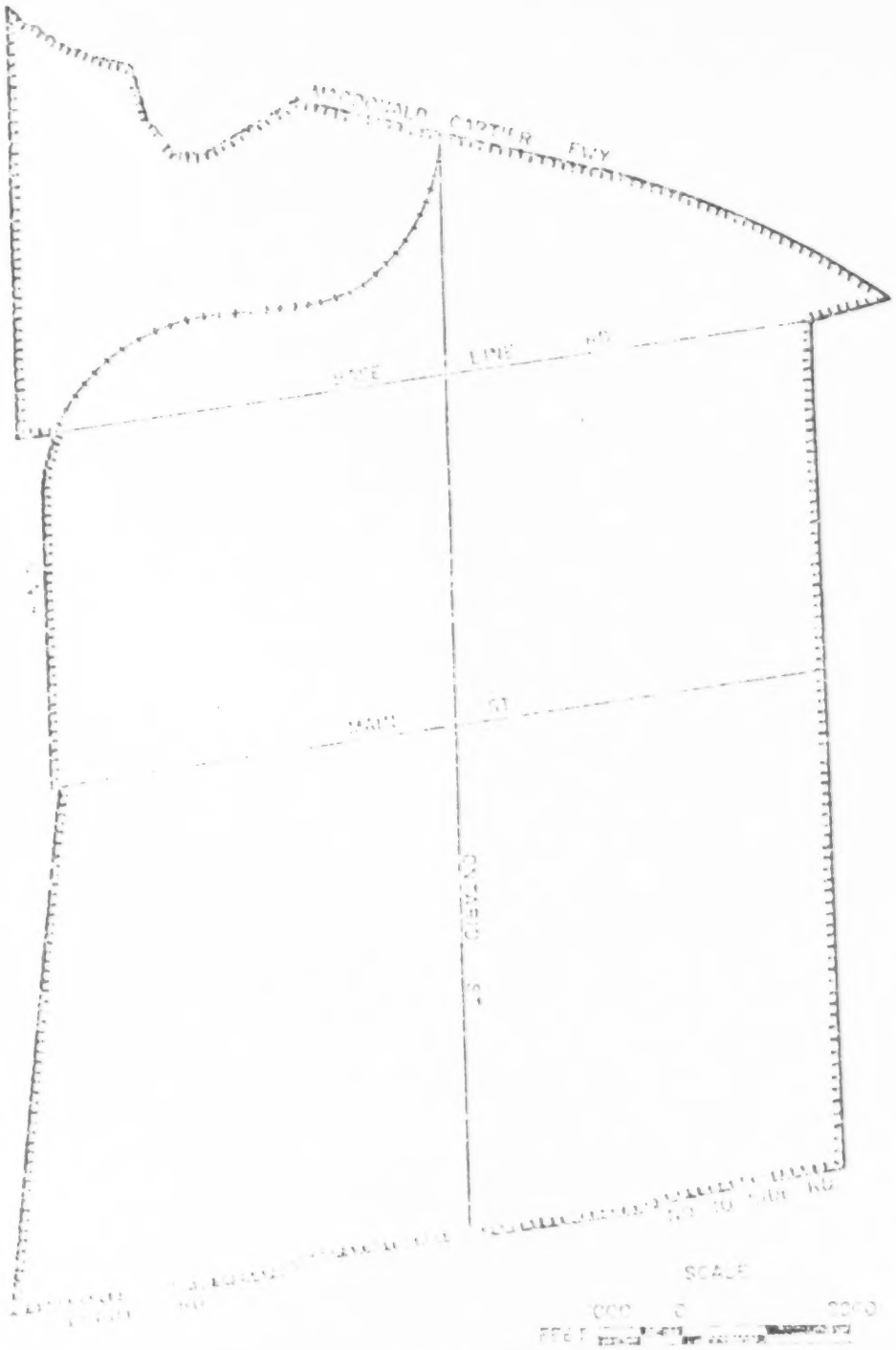

FIGURE 32. AREA OF DATA TABULATION IN MILTON
(inside hatched line)

ST. CATHARINES

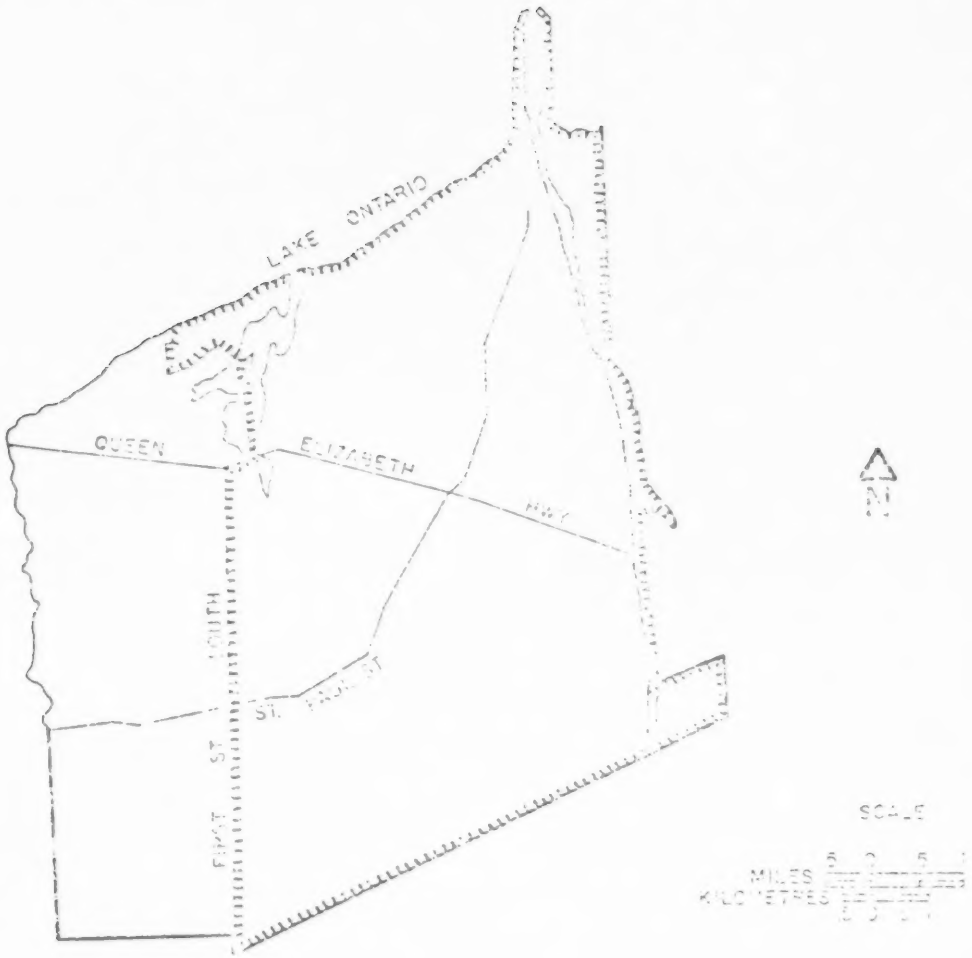

FIGURE 33. AREA OF DATA TABULATION IN ST. CATHARINES
(inside hatched line)

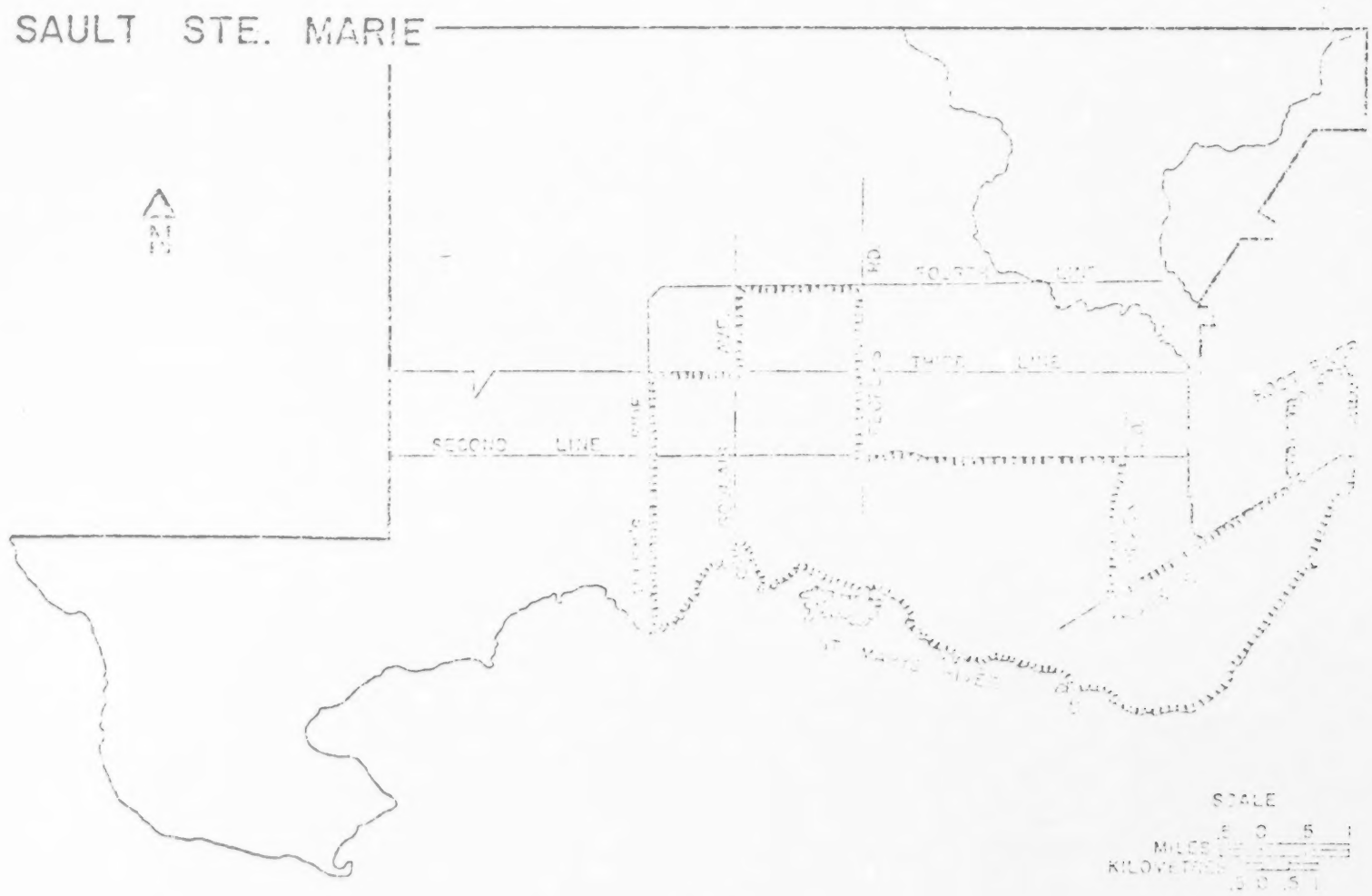

FIGURE 34. AREA OF DATA TABULATION IN SAULT STE. MARIE
(inside hatched line)

APPENDIX III

FIELD INTERVIEW OUTLINE

APPENDIX III

FIELD INTERVIEW OUTLINE

A. General Information

1. Community Information
   a. Demographic - population, land uses, etc.
   b. Community service area
   c. Major economic activities

2. Physical Information
   a. Topographic characteristics
   b. Prevalent soils - permeability, etc.
   c. General patterns of drainage - slopes, location in catchment, etc.

3. Annual Climatic Information
   a. Precipitation - rainfall, snowfall
   b. Temperature distribution, etc.

4. Local Governmental Information
   a. Organization of responsibility for:
      - design and construction of
        - storm runoff works
        - sanitary wastewater works
      - operation and maintenance of
        - storm runoff works
        - sanitary wastewater works

5. Financing for storm and sanitary wastewater works
   a. Local financing methods
   b. Provincial grants
      - administrative vehicle
      - determination of provincial share
      - determination of local share
      - expense attributable to province
      - expense attributable to local jurisdiction
   c. National grants
      - administrative vehicles or agencies involved

- determination of national, provincial, and local shares
- expenses attributable to national, provincial, and local juristictions

d. Past grants experience

B. Collection Systems Information

1. Service area coverage
   a. Combined sewer
   b. Sanitary sewers
   c. Separate storm sewers
   d. Unsewered

2. Mileage of Sewer Systems
   a. Combined sewerage
   b. Sanitary sewerage
   c. Separate storm sewerage

3. Problems Experienced
   a. Hydraulic overloading
   b. System bypasses (and their purpose)
      - number
      - location
      - hydraulic capacity limitation
      - receiving water
   c. System solids deposition problems
      - general location
      - cleaning frequencies
   d. Infiltration and/or inflow
      - roof leader connections
      - other direct inflow locations - manholes, etc.
      - infiltration problems
        - estimated infiltration rates
        - general infiltration problem locations
   e. Storm runoff inundation areas
      - locations
      - cause (no collection systems, hydraulic overloading, etc.)
      - threshold runoff rate that results in inundation problems

4. Local Construction Practice
    a. Use of catch basins or inlets
    b. Construction of system relief bypasses
    c. Control of bypasses or overflows
        - regulators
        - detention facilities
    d. Use of detention facilities
        - Type - on-site, in-system, off-system
        - preferable locations for each type
        - approximate design criteria
    e. Use of retention facilities
    f. Practices concerning extension of combined sewer systems
    g. Practices concerning extension of separate sanitary sewer systems
    h. Practices concerning extension of separate storm sewer systems

C. Dry-Weather Treatment Works
    a. Mean daily flows
    b. Treatment unit processes
    c. Equalization of influent flows
    d. Influent strength
        - BOD
        - COD
        - SS
        - Nutrients
        - Coliform
    e. Treatment removal efficiencies
    f. Effluent strength
    g. Hydraulic treatment plant capacity
    h. Bypass capability
        - how often?
        - bypassing due to?

D. Receiving Waters For:
    1. Runoff discharges
    2. Overland flow
    3. Combined sewer overflow

4. System and plant bypasses
5. Treatment plant effluents

E. Wet Weather

1. Control Activities
   a. Regulator operation and maintenance
2. Sampling Activities
   a. Combined sewer overflows
   b. Urban runoff
   c. Bypasses
3. Planning Activities for:
   a. Control of quantity
   b. Control of quality
   c. Abatement of runoff effects
      - storage/detention
        - types
        - likely locations for each
      - treatment
        - treatment types
          standard - sedimentation, disinfection
          exotic - air flotation, microstrainer, swirl technologies

F. Interest In Runoff Planning

1. Current local activities for investigating runoff-induced problems
   a. Quantity management (flood control, etc.)
   b. Quality management
      - effluents
      - bypasses
      - combined sewer overflows
      - runoff discharges
      - overland runoff flow
2. Does interest exist in locally applied runoff planning tools?
   a. Would the local jurisdiction be able to produce inputs?
   b. Do they have computer capacity?
   c. Would they use Ministry level assistance?

G. Verification of Existing Reduced Data

H. Miscellaneous

1. Land acquisition costs

   a. Central city land costs for

      - residential
      - commercial
      - industrial
      - open space

   b. Non-central city land costs for

      - residential
      - commercial
      - industrial
      - open space
      - undeveloped

APPENDIX IV

PROVINCIAL AND FEDERAL GRANTS

APPENDIX IV

PROVINCIAL GRANTS

All municipalities in the Province of Ontario are eligible under provincial legislation for grants.

I. General grants - These grants are available for general purposes and are not tied to specific uses. Most municipalities use them for relief from taxation by reduction of the mill rate. None of the municipalities interviewed applied for grants for construction and/or maintenance of urban runoff facilities.

II. Subsidy under the Public Transportation and Highway Improvement Act for urban municipalities - The municipalities are eligible for a subsidy allotted annually by the Minister of Transportation and Communications for eligible expenditures made on all roads and streets subject to the limitations of MTC policy on subdivision roads and streets; which limitations are set out in DTC Circular 72-010.

Part I - Construction

A4 Drainage is covered by the subsidy and includes:

(1) Open ditching, including off-take ditches to nearest outlet
(2) Underdrains
(3) Storm sewers, including pumping stations where required, subject to the limitations of MTC policy currently outlined in DTC Circular 71-040
(4) Catch basins and connections
(5) Curbs
(6) Gutters
(7) Municipal drainage assessment on roads
(8) Stream improvement, if required beyond those limits defined in Section B

B. Bridges, culverts, and grade separations subsidizable at bridge and culvert rate.

3. Outlet sewers for underpasses, including pumping stations when required, subject to limitations outlined in DTC Circular 71-040

5. Stream improvement, if required, for 100 feet along bed of stream measured from the outer extremities of a new structure
6. Stream diversion in lieu of structures only if approved by Head Office

Part II - Maintenance

A Roads and Streets

3. Roadside

(1) Entrance culverts - cleaning, repairs
(2) Ditches, including off-take-cleaning, repairs, relocation
(3) Erosion control
(4) Catch basins - cleaning, repairs, replacement
(5) Storm sewers, subject to limitations of MTC policy currently outlined in DTC Circular 71-040
(6) Underdrain cleaning, repairs, replacement
(8) Curb and gutter repairs and replacement
(12) Municipal drainage assessment on roads

B4 Replacement of pipe culvert

Part III - Overhead

Overhead can be compensated for at 7 percent of the cost of items eligible for subsidy under Parts I and II. Details are set forth in Part III of published guidelines.

In DHO OB-M-69 a schedule is set out giving allowable rates for equipment rental.

In Circular No. 71-038 a list of approved protective clothing and safety equipment is given.

Circular 71-040 sets out the subsidy on storm sewer construction and maintenance.

Circular 71-020 outlines the conditions under which the Minister will authorize the payment of subsidy on municipal expenditures made on roads or streets opened or constructed by private interest, or opened or

constructed by municipality acting as a subdivider, or opened or constructed by the municipality acting as a constructor for the subdivider. Three cases are set out and eligibility can be determined by a decision-tree concept graph included therein.

In addition there are certain municipalities, as of April 1, 1975, that are eligible for provincial grants for water and sewage facilities through the Ministry of the Environment:

- Municipality of Metropolitan Toronto
- The Regional Municipalities of
  Durham
  Haldimand-Norfolk
  Halton
  Hamilton-Wentworth
  Niagara
  Ottawa-Carleton
  Peel
  Sudbury
  Waterloo
  York
- The District Municipality of Muskoka
- The cities of Thunder Bay and Timmins

Sewage facilities include all treatment works operated by the municipality or on behalf of an area municipality or any local branch thereof, and intercepting and trunk sanitary sewers including ancillary structures which make practicable the matter of adequate but efficient pollution control (the trunk sewer must terminate at a sewage treatment plant, may serve as a local collector, and must have a theoretical capacity in excess of 6 cfs).

Eligible costs include:

(a) Cost of design and supervision
(b) Actual construction costs incurred by the municipality
(c) Interim financing charges during actual construction
(d) Expenditures incurred in associated land purchases
(e) Other approved costs (savings clause).

FEDERAL GRANTS

Federal grants of interest to municipalities are (1) those administered by the Central Mortgage and Housing Corporation under the terms of the National Housing Act, 1973, and (2) grants administered in the past by different federal departments under the category of Winter Works or Winter Capital Projects Funds for New Employment Opportunities in the Construction Industry. This was to be succeeded by a new Local Initiative Program to reduce seasonally high unemployment in 1976 and 1977, with emphasis being given to municipal works and projects. (Announcement by Minister of Finance in budget speech of June 21, 1975.)

(1) The sections of the National Housing Act noted below are of most interest to municipal and regional public works departments:

Part III - Urban Renewal, Sections 22 through 27

Part III.1 - Neighborhood Improvement Program, Sections 27.1 through 27.6

Part VI.1 - New Communities Federal-Provincial Agreements, Sections 45.1 through 45.3

Part VIII - Loans for Municipal Sewage Treatment Projects, Sections 50 through 54

(2) Federal-Provincial Winter Capital Project Funds

This has been a federally financed program to provide essentially new employment opportunities for people largely in the construction industry.

Capital works programs are those which would not ordinarily have been undertaken. The labor cost forgiveness is 100 percent for employment created between December 1 and May 31 in any year, and 50 percent in the summer season. The program is said to generate up to four times the amount of work (in dollars) of the allotment granted.

The above program has been in effect from time to time since the 1950's. On June 21, 1975, the Federal Minister of Finance announced in his budget speech, that a new Local Initiative Program with available funds up to $285 million was to be set up.

The program would provide for projects over two eight-month segments, November/June 1976 and November/June 1977, to generate 400,000 man-months of employment.

The program would be administered by the Department of Manpower and Immigration, and was being created to reduce high seasonal unemployment in specific areas. It is a labour-intensive community betterment program.

Federal funds will be available for approved projects sponsored by private groups or by municipalities with the emphasis on municipal works and projects.